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TRANSMITTAL FORM

(to be used for all correspondence after initial filing)

Total Number of Pages in This Submission	107

Application Number	10/734,050
Filing Date	December 11, 2003
First Named Inventor	GORDON, Andrew W.
Art Unit	1723
Examiner Name	Krishnan S. Menon
Attorney Docket Number	8021-28

ENCLOSURES *(Check all that apply)*

- [x] Fee Transmittal Form
  - [ ] Fee Attached
- [ ] Amendment/Reply
  - [ ] After Final
  - [ ] Affidavits/declaration(s)
- [ ] Extension of Time Request
- [ ] Express Abandonment Request
- [ ] Information Disclosure Statement
- [ ] Certified Copy of Priority Document(s)
- [ ] Reply to Missing Parts/ Incomplete Application
  - [ ] Reply to Missing Parts under 37 CFR 1.52 or 1.53
- [ ] Drawing(s)
- [ ] Licensing-related Papers
- [ ] Petition
- [ ] Petition to Convert to a Provisional Application
- [ ] Power of Attorney, Revocation Change of Correspondence Address
- [ ] Terminal Disclaimer
- [ ] Request for Refund
- [ ] CD, Number of CD(s) _____
  - [ ] Landscape Table on CD
- [ ] After Allowance Communication to TC
- [ ] Appeal Communication to Board of Appeals and Interferences
- [x] Appeal Communication to TC **(Appeal Notice, Brief, Reply Brief)**
- [ ] Proprietary Information
- [ ] Status Letter
- [x] Other Enclosure(s) (please Identify below):
  - Documents listed in References Appendix
  - Return Receipt Postcard

Remarks

The attached Brief on Appeal (inclusive 2 appendices) is submitted herewith.

SIGNATURE OF APPLICANT, ATTORNEY, OR AGENT

Firm Name	Ruden, McClosky, Smith, Schuster & Russell, P.A.		
Signature	SK		
Printed name	Stanley A. Kim, Ph.D., Esq.		
Date	December 7, 2006	Reg. No.	42,730

CERTIFICATE OF TRANSMISSION/MAILING

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Effective on 12/08/2004.
Fees pursuant to the Consolidated Appropriations Act, 2005 (H.R. 4818).

FEE TRANSMITTAL
For FY 2006

☑ Applicant claims small entity status. See 37 CFR 1.27

TOTAL AMOUNT OF PAYMENT ($) 250.00

Complete if Known	
Application Number	10/734,050
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METHOD OF PAYMENT (check all that apply)

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FEE CALCULATION

1. BASIC FILING, SEARCH, AND EXAMINATION FEES

Application Type	FILING FEES Fee ($)	FILING FEES Small Entity Fee ($)	SEARCH FEES Fee ($)	SEARCH FEES Small Entity Fee ($)	EXAMINATION FEES Fee ($)	EXAMINATION FEES Small Entity Fee ($)	Fees Paid ($)
Utility	300	150	500	250	200	100	
Design	200	100	100	50	130	65	
Plant	200	100	300	150	160	80	
Reissue	300	150	500	250	600	300	
Provisional	200	100	0	0	0	0	

2. EXCESS CLAIM FEES

Fee Description	Fee ($)	Small Entity Fee ($)
Each claim over 20 (including Reissues)	50	25
Each independent claim over 3 (including Reissues)	200	100
Multiple dependent claims	360	180

Total Claims		Extra Claims		Fee ($)		Fee Paid ($)
_____	- 20 or HP =	_____	x	_____	=	_____

HP = highest number of total claims paid for, if greater than 20.

Indep. Claims		Extra Claims		Fee ($)		Fee Paid ($)
_____	- 3 or HP =	_____	x	_____	=	_____

HP = highest number of independent claims paid for, if greater than 3.

Multiple Dependent Claims Fee ($)	Multiple Dependent Claims Fee Paid ($)
_____	_____

3. APPLICATION SIZE FEE

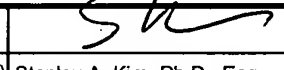
If the specification and drawings exceed 100 sheets of paper (excluding electronically filed sequence or computer listings under 37 CFR 1.52(e)), the application size fee due is $250 ($125 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s).

Total Sheets		Extra Sheets		Number of each additional 50 or fraction thereof		Fee ($)		Fee Paid ($)
_____	- 100 =	_____	/ 50 =	_____	(round **up** to a whole number) x	_____	=	_____

4. OTHER FEE(S)

	Fees Paid ($)
Non-English Specification, $130 fee (no small entity discount)	
Other (e.g., late filing surcharge): Statutory fee for filing Brief on Appeal	250.00

SUBMITTED BY

Signature		Registration No. (Attorney/Agent) 42,730	Telephone 561-838-4512
Name (Print/Type)	Stanley A. Kim, Ph.D., Esq.		Date December 7, 2006

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
Before the Board of Patent Appeals and Interferences

In re: Application of GORDON, Andrew W.

Application No.:	10/734,050	Examiner:	Krishnan S. Menon
Date filed:	December 11, 2003	Art Unit:	1723

For: MOBILE DESALINATION PLANTS AND SYSTEMS, AND METHODS FOR PRODUCING DESALINATED WATER

CERTIFICATE UNDER 37 CFR 1.8(A)
I hereby certify that this correspondence is deposited with the United States Postal Service with sufficient postage, as express mail, label no. EV 745414721, addressed to Commissioner for Patents, P.O. Box 1450, Alexandria, VA, 22313-1450 on December 7, 2006.

_____, Reg. No. 42,730
Stanley A. Kim, Ph.D., Esq.

APPELLANT'S BRIEF ON APPEAL

Mail Stop: Appeal Brief - Patents
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

Appellant, having filed a timely Notice of Appeal in the above-identified patent application, hereby submits this brief.

12/08/2006 HVUONG1 00000088 503110 10734050
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I. Real Party in Interest

The real party in interest in this application is Water Standard Company, LLC.

II. Related Appeals and Interferences

There are no related appeals or interferences.

III. Status of Claims

Claims 1-14 were included in the application when filed. In appellant's June 12, 2006 amendment, claims 1-14 were canceled and new claims 15-36 were added. In appellant's July 27, 2006 amendment, claim 29 was canceled; claims 15, 28, and 30 were amended; and new claims 37-41 were added. Accordingly, claims 15-28 and 30-41 are presently pending in the application. In the latest office action, which was mailed on October 13, 2006, claims 27 and 36 were allowed, claim 26 was objected to but indicated to be allowable, and claims 15-25, 28, 30-35, and 37-41 were rejected.

This appeal is taken with respect to pending claims 15-25, 28, 30-35, and 37-41, which are set forth in the Claims Appendix attached hereto.

IV. Status of Amendments

No amendments have been filed subsequent to the latest office action from which this appeal is taken.

V. Summary of the Claimed Subject Matter

Independent claims 15, 27, and 28 are involved in this Appeal.

Independent claim 15 is directed to a system for desalinating seawater to yield desalinated water and a concentrate (Fig. 13, 1301, Fig. 16, 1601, and paragraphs [0023], [0099], [0111], [0122], [0155], and [0222]). The system comprises a first sea-going vessel comprising a hull and being positioned on the surface of a body of seawater (Fig. 1, 101, Fig. 3, 101, Fig. 4, 101, Fig. 6, 101, Fig. 7, 101, Figs. 10-12, 101, Fig. 13, 1310, Fig. 14, 1310, Fig. 15, 1510, Fig. 16, 1610, and paragraphs [0019], [0032], [0131], [0140], [0142], [0144], and [0182]); a water desalination system installed on the first sea-going vessel (Fig. 1, 104, Fig. 2, 200, and paragraphs [0099], [0100], [0113], and [0155]), the water desalination system capable of removing salt from seawater (paragraphs [0031], [0099], [0111], [0122], [0155], and [0163]); a water intake system installed on the first sea-going vessel and comprising an apparatus for taking up seawater from the body of seawater (Fig. 1A, 202, 203, Fig.2, 201, Fig. 3, 202, and paragraphs [0100], [0103], [0131], [0156], [0157] and [0159]-[0161]), the apparatus comprising at least one water intake positioned in the body of seawater at a first depth (Fig. 6B, 201, Fig. 28, 201, and paragraphs [0131], [0156], and [0157]); and a mixing system for mixing the concentrate with seawater to yield a diluted concentrate (Fig. 9, 905, and paragraphs [0024], and [0144]-[0150]), the mixing system being installed on the first sea-going vessel in communication with the water desalination system (paragraphs [0130], [0144], and [0150]). The mixing system includes a space in which concentrate can be mixed with seawater to form the diluted concentrate, an inlet for introducing concentrate into the space, an inlet for introducing seawater into the space, and an outlet for discharging the diluted concentrate from the space (Fig. 9, 905,

and paragraphs [0145], [0146], [0170], and [0192]); and a concentrate discharge system for discharging the diluted concentrate from the first sea-going vessel (Fig. 2, 207, Fig. 4, 207, Fig. 7, 207, Fig. 8, 207, Fig. 28, 207, and paragraphs [0119]-[0124], [0132]-[0134], and [0137]), the concentrate discharge system being installed on the first sea-going vessel (Fig. 4, 207, Fig. 6, 207, Fig. 7, 207, Fig. 28, 207, and paragraphs [0122], [0128], [0129] and [0168]). The concentrate discharge system comprises at least one discharge port being positioned at a site not at the first depth (Fig. 6B, 201, 207, Fig. 28, 201, 207, and paragraphs [0131], [0156], and [0157]).

Independent claim 27 is directed to a system for desalinating seawater to yield desalinated water and a concentrate (Fig. 13, 1301, Fig. 16, 1601, and paragraphs [0023], [0099], [0111], [0122], [0155], and [0222]) comprising a first sea-going vessel being positioned on the surface of a body of seawater (Fig. 1, 101, Fig. 3, 101, Fig. 4, 101, Fig. 6, 101, Fig. 7, 101, Figs. 10-12, 101, Fig. 13, 1310, Fig. 14, 1310, Fig. 15, 1510, Fig. 16, 1610, and paragraphs [0019], [0032], [0131], [0140], [0142], [0144], and [0182]); a water desalination system installed on the first sea-going vessel (Fig. 1, 104, Fig. 2, 200, and paragraphs [0099], [0100], [0113], and [0155]) and capable of removing salt from seawater to yield desalinated water and a concentrate (paragraphs [0031], [0099], [0111], [0122], [0155], and [0163]); a water intake system installed on the first sea-going vessel in fluid communication with the water desalination system and comprising an apparatus for taking up seawater from the body of seawater (Fig. 1A, 202, 203, Fig.2, 201, Fig. 3, 202, and paragraphs [0100], [0101], [0103], [0110], [0131], [0156], [0157] and [0159]-[0161]), the apparatus positioned in the body of seawater at a first depth relative to

the surface of the body of seawater (Fig. 6B, 201, Fig. 28, 201, and paragraphs [0131], [0156], and [0157]); and a concentrate discharge system for discharging the concentrate from the first sea-going vessel (Fig. 2, 207, Fig. 4, 207, Fig. 7, 207, Fig. 8, 207, Fig. 28, 207, and paragraphs [0119]-[0124], [0132]-[0134], and [0137]), the concentrate discharge system being installed on the first sea-going vessel in fluid communication with the water desalination system (Fig. 4, 207, Fig. 6, 207, Fig. 7, 207, Fig. 28, 207, and paragraphs [0101], [0121], [0122], [0128], [0129] and [0168]). The concentrate discharge system comprises at least one discharge member positionable in the body of seawater (Fig. 6A, 207, Fig. 6B, 201, 207, Fig. 7, 207, Fig. 28, 201, 207, and paragraphs [0128]-[0132], [0156], and [0157]). The at least one discharge member comprises (a) a conduit through which concentrate can flow from the water desalination system to the body of seawater and (b) an aspirator through which seawater from the body of seawater can be drawn into the discharge member to mix with concentrate in the conduit (Fig. 2, 206, 207, and paragraphs [0130], [0134], and [0145]).

Independent claim 28 is directed to a method of desalinating seawater on a sea-going vessel positioned on the surface of a body of seawater (Fig. 23, 2310, and paragraphs [0023], [0027], [0035], and [0162]-[0168]). The method comprises the steps of intaking seawater from the body of seawater at a first depth into the vessel (Fig. 6B, 201, Fig. 28, 201, and paragraphs [0131], [0156], and [0157]); removing salt from the seawater taken into the vessel to yield desalinated water and a concentrate (paragraphs [0031], [0099], [0111], [0122], [0155], and [0163]); diluting the concentrate with seawater to yield a diluted concentrate (Fig. 9, 905, and paragraphs [0024], and [0144]-[0150]); and discharging the diluted concentrate into the body of

seawater at a site not at the first depth (Fig. 6B, 201, 207, Fig. 28, 201, 207, and paragraphs [0131], [0156], [0157], and [0169]-[0171]).

VI. Grounds of Rejection to be Reviewed on Appeal

A. Whether claims 24 and 25 were properly rejected under the enablement requirement of 35 U.S.C. §112, first paragraph.

B. Whether claims 15-26, 28, and 30-35 were properly rejected under the written description requirement of 35 U.S.C. §112, first paragraph.

C. Whether claims 15, 28, and 30 were properly rejected under 35 U.S.C. §102(e) as being anticipated by, or under 35 U.S.C. §103(a) as being obvious over Krylov (U.S. Patent No. 6,658,889).

D. Whether claims 28, 31, and 32 were properly rejected under 35 U.S.C. §103(a) as being unpatentable over Bosley (U.S. Patent No. 6,348,148).

E. Whether claims 15-23, 28, 30-35, and 37-41 were properly rejected under 35 U.S.C. §103(a) as being unpatentable over Lampe et al. ("PCS-Preussag Conversion Systems", Elsevier, 1997), in view of Permar (U.S. Patent No. 6,299,766) and/or Bosley (U.S. Patent No. 6,348,148).

VII. Argument

A. The enablement rejections of claims 24 and 25 are erroneous because instruments and sensors for determining the depth of a thermocline or plankton in a body of water were well known at the time the application was filed.

Claims 24 and 25 stand rejected under 35 U.S.C. §112, first ¶ for allegedly not providing sufficient details of the instruments and sensors for one of ordinary skill in the art to determine the depth of a thermocline or plankton in a body of water. Claims 24 and 25 recite:

> 24. The system of claim 15, wherein the first sea-going vessel comprises instrumentation and sensors for detecting the presence of and depth of thermoclines in the body of seawater.
>
> 25. The system of claim 15, wherein the first sea-going vessel comprises instrumentation and sensors for detecting the presence of and depth of plankton in the body of seawater.

The specification describes these limitations in paragraph [161].

In addressing these rejections, appellant previously argued that such systems were well known at the time the application was filed[1] and cited several references[2] (attached hereto) to illustrate this point. In maintaining the rejection, the examiner responded that the cited references were not well known in the art of desalination, that US 5,834,641 does not detect

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[1] A patent need not teach, and preferably omits, what is well known in the art. (In re Buchner, 929 F.2d 660, at 661, 18 USPQ2d 1331, at 1332 (Fed. Cir. 1991); Hybritech, Inc. v. Monoclonal Antibodies, Inc., 802 F.2d 1367, 1384, at 231 USPQ 81, at 94 (Fed. Cir. 1986), cert. denied, 480 U.S. 947 (1987); Lindemann Maschinenfabrik GMBH v. American Hoist & Derrick Co., 730 F.2d 1452, at 1463, 221 USPQ 481, at 489 (Fed. Cir. 1984)).

[2] I.e., US 5,834,641; Ashjian et al., "Distribution of plankton, particles, and hydrographic features across Georges Bank described using the Video Plankton Recorder." Deep-Sea Research Part II-Topical Studies in Oceanography. 48 (1-3), 2001; Benfield et al. "ZOOVIS: a high resolution digital camera system for quantifying zooplankton abundance and environmental data". American Society of Limnology and Oceanography, 2001 Aquatic Sciences Meeting, Albuquerque, NM, February 12-17, 2001; Davis et al. "Microaggregations of Oceanic Plankton Observed by Towed Video Microscopy", Science 257, 1992; and Flagg and Smith, "On the use of the Acoustic Doppler current profiler to measure zooplankton abundance," Deep Sea Res. 36, 1989.

plankton, and that appellant "...had neither incorporated (or quoted) this reference in the specification...nor provided this reference in an IDS with the filing of the application, which makes one wonder whether the applicant knew about this reference at the time of filing the application."

In describing the test for enablement, MPEP 2164.01 states "[a]ny analysis of whether a particular claim is supported by the disclosure in an application requires a determination of whether that disclosure, when filed, contained sufficient information regarding the subject matter of the claims as to enable one skilled in the pertinent art to make and use the claimed invention" without undue experimentation.[3] Regarding inventions spanning multiple arts, "...the specification is enabling if it enables persons skilled in each art to carry out the aspect of the invention applicable to their specialty."[4]

In arguing that the supporting references are not in the field of desalination or membrane separation, the examiner has erroneously characterized the invention as falling into only a single art. Referring to the language of claims 24 and 25, it is readily apparent that the invention concerns not only the field of desalination, but also the field of detecting thermoclines/plankton from a sea-going vessel. The supporting references show that vessel-based thermocline and

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[3] See, In re Wands, 858 F.2d at 737, 8 USPQ2d at 1404 (Fed. Cir. 1988).

[4] In re Naquin, 398 F.2d 863, 866, 158 USPQ 317, 319 (CCPA 1968); see also, Technicon Instruments Corp. v. Alpkem Corp., 664 F. Supp. 1558, 1578, 2 USPQ2d 1729, 1742 (D. Ore. 1986) ("If two distinct technologies are relevant to an invention, then the disclosure will be adequate if a person of ordinary skill in each of the two technologies could practice the invention from the disclosures."), aff'd in part, vacated in part, rev'd in part, 837 F. 2d 1097 (Fed. Cir. 1987) (unpublished opinion), appeal after remand, 866 F. 2d 417, 9 USPQ 2d 1540 (Fed. Cir. 1989); Ex parte Zechnall, 194 USPQ 461 (Bd. App. 1973) ("appellants' disclosure must be held sufficient if it would enable a person skilled in the electronic computer art, in cooperation with a person skilled in the fuel injection art, to make and use appellants' invention.").

plankton detection were well known in this field. Utilizing the specification as a guide, because such technology was well known at the time the application was filed, it would not require undue experimentation for a specialist in the art of vessel-based thermocline and plankton detection to install known "...instrumentation and sensors for detecting the presence of and depth of thermoclines [or plankton]" on the subject sea-going vessels.

The examiner's argument that US 5,834,641 does not describe plankton detection obscures appellant's point and is irrelevant to the enablement rejection. As appellant clearly pointed out in his July 27, 2006 amendment and his August 29, 2006 Arguments for the Pre-Appeal Brief Conference, US 5,834,641 relates to claim 24's detecting thermoclines, not claim 25's detecting plankton. To clarify, the other supporting references relate to plankton detection, not thermocline detection. These references were cited merely as examples of documents showing that vessel-based plankton/thermocline detection was well known prior to appellant's filing date.

The examiner's argument that appellant "...had neither incorporated (or quoted) this reference [US 5,834,641] in the specification...nor provided this reference in an IDS with the filing of the application, which makes one wonder whether the applicant knew about this reference at the time of filing the application...." is also improper[5] and irrelevant to the enablement rejection. Appellant is unsure of the purpose of the examiner's statement, but remains unaware of any statute or regulation that requires US 5,834,641 to be incorporated or quoted in the specification, to be disclosed in an IDS, or to have even been known to appellant at the time of filing.

[5] See MPEP 707.07(d)

B. The written description rejections of claims 15-26, 28, and 30-35 are erroneous because the site of concentrate discharge is adequately described in the application.

Claims 15-26, 28, and 30-35 stand rejected for failing to meet the written description requirement of 35 U.S.C. §112, first ¶ because the limitation "not at the first depth" was alleged to "not seem to have support in the original disclosure." The pertinent part of independent claim 15 (from which claims 16-26 depend) recites:

> 15. A system for desalinating seawater to yield desalinated water and a concentrate, the system comprising:
>
> ...
>
> a water intake system installed on the first sea-going vessel and comprising an apparatus for taking up seawater from the body of seawater, the apparatus comprising at least one water intake positioned in the body of seawater at a first depth;
>
> ...
>
> a concentrate discharge system for discharging the diluted concentrate from the first sea-going vessel, the concentrate discharge system being installed on the first sea-going vessel and comprising at least one discharge port being positioned at a site not at the first depth.

The pertinent part of claim 28 (from which claims 30-35 depend) recites:

> 28. A method of desalinating seawater on a sea-going vessel positioned on the surface of a body of seawater, the method comprising the steps of:
>
> intaking seawater from the body of seawater at a first depth into the vessel
>
> ...
>
> discharging the diluted concentrate into the body of seawater at a site not at the first depth.

In his first argument, the examiner cited MPEP 2173.05(i) regarding negative limitations, but did not provide further explanation. MPEP 2173.05(i), citing Ex parte Parks,[6] states "... a lack of *literal* basis in the specification for a negative limitation may not be sufficient to establish a prima facie case for lack of descriptive support." Although the exact words "not at the first

[6] 30 USPQ2d 1234, 1236 (Bd. Pat. App. & Inter. 1993) ("...it is sufficient if the originally-filed disclosure would have conveyed to one having ordinary skill in the art that an appellant had possession of what was claimed.").

depth" may not appear in the specification as filed, satisfying the written description requirement does not require *in haec verba* antecedence.[7] Rather, satisfying the written description requirement merely requires that the originally filed application convey to a person of ordinary skill in the art that the applicant invented the subject matter later claimed.[8] In other words, written description support for an element occurring in claim exists if the concept (and not necessarily the exact words) of the element is adequately described in the originally filed application.

The concepts of (i) a discharge port being located at a different depth than a seawater intake and (ii) a step of discharging diluted concentrate a depth differing from the depth of seawater intake are both more than adequately described in the originally filed application. As an example, these concepts are described at Figs. 6B and 28; paragraphs [128], [131], [156], [157]; and original claims 1 (discharge deeper than intake) and 4 (intake deeper than discharge). Moreover, the application teaches the general concept that positioning an intake and discharge at different depth levels (i.e., intake at a first depth and discharge a site not at the first depth) reduces or eliminates the uptake of discharged concentrate into the water purification system. Clearly, based on this teaching in the originally filed application, one of skill in the art would readily understand that appellant was in possession of these concepts.

In a second argument, the examiner stated that "there is no support for the possibility that the concentrate discharge is in the air, sprayed from the ship into the air 10 ft above the ocean

[7] In re Lukach, 440 F.2d 1263, 169 USPQ 795 (CCPA 1971).
[8] In re Smythe, 480 F.2d 1376, 178 USPQ 279 (CCPA 1973).

surface."[9] In making this statement, the examiner appears to imply that the written description requirement requires an applicant to describe the details of each and every different possible variation and nuance of a claimed invention. According to MPEP 2163, however, "[i]f a skilled artisan would have understood the inventor to be in possession of the claimed invention at the time of filing, *even if every nuance of the claims is not explicitly described in the specification*, then the adequate description requirement is met."[10] In cases involving generic claim elements in predictable arts, strict application of the written description requirement could lead to ludicrous results. For example, in the present case, must the specification also have described concentrate discharge on a mountain top and on the moon in order to provide adequate written description support for the step of discharging concentrate at a depth differing from the depth of seawater intake?

C. Claims 15, 28, and 30 are neither anticipated by or obvious over Krylov (U.S. Patent No. 6,658,889) because Krylov fails to expressly or inherently teach or suggest a concentrate discharge port or discharge of diluted concentrate.

Claims 15, 28, and 30 stand rejected as being anticipated by or obvious over Krylov. A rejection of these claims based on §102 or §103 is clearly improper because Krylov fails to teach or suggest limitations present in independent claims 15 and 28 (from which claim 30 depends). For example, claim 15 recites "a concentrate discharge system ... comprising at least one discharge port," and claim 28 recites a step of "...discharging the diluted concentrate into the

[9] Note that the application at Fig. 4 and paragraph [122] describes an embodiment similar to that proposed by the examiner.

[10] See also, Vas-Cath, Inc. v. Mahurkar, 935 F. 2d 1555, 1563-64 (Fed. Cir 1991).

body of seawater at a site not at the first depth." Krylov does not describe or suggest either a discharge port or a discharge step (of either undiluted or diluted concentrate).

Although Krylov is completely silent on concentrate discharge, the examiner contends that the subject limitations are inherent. The examiner, however, has not met the burden of proof required to show inherency because he has not provided any evidence whatsoever showing that concentrate discharge would necessarily flow from Krylov, or that such discharge would necessarily be into a body of seawater (claim 28) or via a discharge port (claim 15).[11]

A second error relating to this rejection is that the examiner has repeatedly not addressed the substance of applicant's argument as is required by 37 CFR §1.104 (see also MPEP §707.07(f)). In the office actions dated August 8, 2006 and October 13, 2006, the examiner's entire response to appellant's repeated arguments that the examiner has failed to provide any evidence whatsoever that the allegedly inherent characteristic necessarily flows from Krylov and that several alternative possibilities exist,[12] was the conclusory statement:

> With respect to the Krylov reference, discharging the concentrate to the ocean would not constitute a patentable limitation over the reference. Discharging the concentrate is an inherent or implied teaching in the reference, as shown.

In repeatedly refusing to address the substance of appellant's argument, the examiner has

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[11] MPEP §2112 indicates " '[i]n relying upon the theory of inherency, the examiner must provide a basis in fact and/or technical reasoning to reasonably support the determination that the allegedly inherent characteristic necessarily flows from the teachings of the applied prior art.' Ex parte Levy, 17 USPQ2d 1461, 1464 (Bd. Pat. App. & Inter. 1990)" and "[t]he fact that a certain result or characteristic may occur or be present in the prior art is not sufficient to establish the inherency of that result or characteristic. In re Rijckaert, 9 F.3d 1531, 1534, 28 USPQ2d 1955, 1957 (Fed. Cir. 1993)."

[12] See appellant's July 27, 2006 Amendment ("First, Krylov's ice slush might never be discharged of at all. For example, Fig. 9 suggests that melted ice slush is routed from the fish holding compartment to the ice slush tube for refreezing. Second, even if it could be definitively proven that the ice slush was discharged, such discharge might be into a land-based facility rather than a body of seawater. Land-based disposal is the most logical inference from Krylov because, for the purpose of preserving freshness, it would be desirable to keep the ice slush in contact with the fish even after off-loading to a land-based facility. Third, referring back to the first point, if no discharge was contemplated, then no discharge port would be required. And even if discharge was contemplated, various means other than a discharge port could be used, e.g., a bucket attached to rope which could be manually operated by a person on Krylov's vessel.").

failed to meet the requirement of rule 104, delaying prosecution of this application and necessitating this appeal.

D. The rejection of claims 28, 31, and 32 under 35 U.S.C. §103 over Bosley (U.S. Patent No. 6,348,148) is erroneous because Bosley fails to teach or suggest (i) discharging *diluted* concentrate and (ii) desalination on a sea-going vessel positioned on the surface of a body of seawater.

Claims 28, 31, and 32 stand rejected under 35 U.S.C. §103 for allegedly being obvious over Bosley. This rejection is erroneous because the examiner has failed to establish a prima facie case of obviousness as Bosley fails to teach or suggest all the claim limitations at issue.[13] The examiner's entire argument in support of this rejection was:

> Bosley teaches a continuous process for making desalinated water by reverse osmosis (abstract, figures) from seawater. The system is offshore, on a ship (column 4 line 65 teaches the system suspended from a ship, which would be 'on a ship' (during examination, the claims must be interpreted as broadly as their terms reasonably allow. In re American Academy of Science Tech Center, _____ F.3d _____, 2004 WL 1067528 (Fed. Cir. May 13, 2004) (The USPTO uses a different standard for construing claims than that used by district courts; during examination the USPTO must give claims their broadest reasonable interpretation)); comprises a vessel (50) for producing a permeate (column 5 lines 4-67), concentrate discharge below the thermocline (lines 35 and 58), intake (column 5 lines 25-33), the intake of seawater and the discharge of concentrate at different levels, permeate delivery means comprises pipeline, transfer pumps, second vessel, etc: see column 5 lines 36-48.
>
> Depth of intake to avoid planktons: Bosley has the system operating at a depth, not at the surface, which would inherently avoid planktons.
>
> Bosley teaches mixing concentrate with seawater at the point of discharge for dilution – column 4 lines 1-20, which is an obvious equivalent of applicant's claim of diluting the concentrate and then discharging into a body of seawater.

[13] See, *In re Royka*, 490 F.2d 981, 180 USPQ 580 (CCPA 1974) (All the claim limitations must be taught or suggested by the prior art to establish prima facie obviousness).

Claim 28, from which claims 31 and 32 depend, recites:

> 28. A method of desalinating seawater on a sea-going vessel positioned on the surface of a body of seawater, the method comprising the steps of:
>
> intaking seawater from the body of seawater at a first depth into the vessel;
>
> removing salt from the seawater taken into the vessel to yield desalinated water and a concentrate;
>
> diluting the concentrate with seawater to yield a diluted concentrate;
>
> discharging the diluted concentrate into the body of seawater at a site not at the first depth.

Claim limitations that Bosley fails to teach or suggest include (i) diluting the concentrate with seawater prior[14] to the step of discharging, (ii) discharging diluted concentrate into the body of seawater, and (iii) desalinating water "on a sea-going vessel positioned on the surface of a body of seawater." The examiner concluded that limitations (i) and (ii) are obvious equivalents of Bosley's mixing concentrate with seawater *at the point* of discharge, but did not provide the required evidence showing that the alleged equivalency was recognized in the prior art.[15] The examiner also did not respond to appellant's evidence[16] and argument that active concentrate dilution before discharge is advantageous in protecting the marine environment and not equivalent to passive concentrate dilution after discharge. Further, the examiner failed to meet the requirement of rule 104 by repeatedly refusing to address the substance of appellant's argument.[17]

Regarding limitation (iii), the examiner argued that Bosley's "...system suspended from a

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[14] I.e., if diluted concentrate is discharged, a step of diluting the concentrate must occur prior to discharge.

[15] See, In re Ruff, 256 F.2d 590, 118 USPQ 340 (CCPA 1958) ("In order to rely on equivalence as a rationale supporting an obviousness rejection, the equivalency must be recognized in the prior art, and cannot be based on applicant's disclosure or the mere fact that the components at issue are functional or mechanical equivalents.")

[16] See e.g., paragraphs [0039] and [0040] of the specification.

[17] Despite appellant making arguments similar to the foregoing in his July 27, 2006 amendment and August 29, 2006 arguments for the pre-appeal brief conference, rather than providing evidence supporting that the alleged equivalency was recognized in the prior art, the latest two office actions simply rehash (almost verbatim) the conclusory argument used in the examiner's initial rejection set forth in the June 20, 2006 office action.

ship...would be '<u>on</u>[18] a ship'" as recited in claim 28. This argument is erroneous because Bosley fails to teach or suggest claim 28's desalination "*...on a sea-going vessel positioned on the surface of a body of seawater.*" Bosley teaches a reverse osmosis system 50 (which the examiner confusingly renames *vessel 50*) which performs desalination at least several fathoms *under* the surface of a body of seawater so that the water pressure at that deep location can drive the reverse osmosis step. In comparison, claim 28's desalination step is performed on a *sea-going vessel* positioned *on the surface* of a body of seawater (e.g., on a ship floating on the surface of the ocean). And even if one were to move Bosley's reverse osmosis system to the surface, it could not operate as the required water pressure would be absent. Accordingly, Bosley cannot be said to teach or suggest claim 28's "...desalinating seawater on a sea-going vessel positioned on the surface of a body of seawater."

E. The rejection of claims 15-23, 28, 30-35, and 37-41 under 35 U.S.C. §103 as being unpatentable over Lampe et al. ("PCS-Preussag Conversion Systems", Elsevier, 1997), in view of Permar (U.S. Patent No. 6,299,766) and/or Bosley is erroneous because the combination of references fails to teach all claim limitations.

Claims 15-23, 28, 30-35, and 37-41 stand rejected under 35 U.S.C. §103(a) as being unpatentable over the combination of Lampe, Permar, and/or Bosley. After struggling with the words in the latest office action, appellant does not believe it clearly communicates the bases of the rejection because the examiner does not directly compare the words of the subject claim limitations with what is described in the cited references. Instead, the examiner describes his

[18] In view of a previous rejection on a similar basis where appellant used the phrase "*aboard* a sea-going vessel," claim 28 was amended to recite "<u>on</u> a sea-going vessel" and appellant also expressly stated on the record that the amendment was to clarify that the claims were not intended to encompass a method utilizing Bosley's device secured to a location in a body of water by cables attached to ships.

very general interpretation of what the claimed subject matter is and how the references pertain to this generalization. The examiner also rejected several claims without providing any reason whatsoever. Accordingly, this rejection also fails to meet the requirement of rule 104.

For the purpose of this appeal, appellant understands that the examiner is alleging that the rejected claims are obvious over the combination of Lampe and Bosley, the combination of Lampe and Permar, and/or the combination of Lampe, Permar, and Bosley. This rejection was originally based on just the combination of Lampe and Bosley. Permar was added in the latest office action, although the examiner's argument appears to indicate that the Lampe/Bosley rejection was maintained. Each of the combinations is discussed below.

The Lampe/Bosley Combination fails to teach or suggest all claim limitations

Independent claim 15 (from which claims 16-23, 37, and 38 depend) recites the claim limitation:

> a mixing system ... installed on the first sea-going vessel ... and comprising a space in which concentrate can be mixed with seawater to form the diluted concentrate, an inlet for introducing concentrate into the space, an inlet for introducing seawater into the space, and an outlet for discharging the diluted concentrate from the space;

Independent claim 28 (from which claims 30-35 and 39-41 depend) recites the claim limitation "...discharging the diluted concentrate into the body of seawater at a site not at the first depth." As appellant previously argued, neither Lampe nor Bosley teach or suggest these limitations.[19]

In the current office action, the examiner responded the foregoing argument with the statement:

> With respect to the rejection of the claims over Lampe in view of Bosley, the "space for mixing" is not a patentable invention. It does not provide

[19] See In re Vaeck, 947 F.2d 488, 20 USPQ2d 1438 (Fed. Cir. 1991) (Among the criteria for establishing a prima facie case of obviousness, the combined prior art references must teach or suggest all claim limitations).

> any particular structure to differentiate the claimed invention from the teaching of the reference. Applicant's mixing of concentrate with seawater before discharge, the point of discharge and the relative dimensions, etc., would not constitute patentable inventions over the references over the references because the references in combination already identifies the problem addressed by the invention and teaches a solution to the problem which is an obvious equivalent of the claimed invention. Attorney's argument in this matter is not sufficient to overcome the rejection. Applicant must provide secondary evidence to prove that applicant's invention is patentable over the combined teaching of the references.

The foregoing statement is legally incorrect for a number of reasons.

First, the examiner erroneously argues that *individual limitations* (the space for mixing, mixing of concentrate with seawater before discharge, the point of discharge, and the relative dimensions) in the claims are not patentable. Appellant never claimed such limitations by themselves, but rather in the context of claims containing multiple limitations. In assessing the patentability of a claim, it is well-settled law that all limitations in that claim must be evaluated – not just one.

Second, Appellant disagrees with the examiner's statement that the "space for mixing" does not provide any particular structure to differentiate the claimed invention from the teaching of the reference. If the examiner is arguing that holes, voids, and spaces are not proper claim limitations, this is not the law.[20] A mixing space clearly is a physical thing that imparts a further limitation to claim 15 and is in no way difficult to detect in mechanical devices. Because neither Lampe nor Bosley teach a "space for mixing," the rejection is erroneous because the relied upon references do not teach or suggest this limitation.

Third, the examiner's argument that the rejected claims are unpatentable because the references in combination already identify the problem addressed by the invention and teach a

[20] See In re Newton, 414 F.2d 1400, 163 USPQ 34 (CCPA 1969).

solution to the problem which is an obvious equivalent of the claimed invention is erroneous. Numerous problems in all of the technical arts have known solutions. The law does not provide that once a solution to a problem is found that no other solutions to the particular are patentable.

The examiner's assertion that Appellant's solution to the problem is an obvious equivalent of what Bosley teaches is simply a conclusory statement unsupported by any evidence whatsoever. In fact, if anything, because Bosley proposes using mid-ocean currents to disperse undiluted concentrate, a skilled artisan in this field would have little reason or motivation to attempt to develop another solution to the problem. Thus, the most that the Bosley/Lampe combination suggests is to run a concentrate discharge pipe from a ship having a desalination system thereon. This combination achieves the goals of Lampe's and Bosley's systems, but in no way suggests appellant's innovation of pre-dilution of concentrate before discharge. Hereto, in contravention of rule 104, the examiner again simply ignored Appellant's prior arguments[21] of the advantages offered by diluting concentrate with seawater prior to discharge as compared to Bosley's dumping of *undiluted* concentrate directly into a mid-water location in a body of water for dispersion by ocean current.

Fourth, the examiner's requirement that appellant "...must provide secondary evidence to prove that applicant's invention is patentable over the combined teaching of the references" is also believed to be erroneous as appellant is unaware of any requirement that a patent applicant produce secondary evidence to establish patentability.

Regarding the rejected claims that depend from claims 15 and 28, the examiner admits

[21] See page 3 of Appellant's Argument for Pre-Appeal Brief Conference and page 14 of Appellant's July 27, 2006 Amendment ("Applicant's method allows significantly more control over the concentrate dilution process and thereby significantly more control over mitigating damage to the environment. This advantage is particularly important on a sea-going vessel-based desalination system that might operate at different locations having different geographies, some of which might not allow placement of a discharge pipe at a mid-water location (e.g., at a shallow location near shore) or at a location which exposes the discharged undiluted concentrate to an ocean current of sufficient strength to promote sufficient mixing to mitigate environmental damage.")

that the combination of Lampe and Bosley fails to teach a number of the limitations recited therein,[22] but argues that the missing limitations each have equivalents described in Bosley and that in view of In re Fout,[23] Lampe and Bosley need not expressly suggest substituting the alleged equivalent components. Applicant disagrees with this argument for the reasons presented below.

Claim 16 recites "...the first sea-going vessel has a draught of more than 10 meters and the apparatus for taking up seawater from the body of seawater comprises a sea chest formed in the lower portion of the hull of the first sea-going vessel." Neither Lampe nor Bosley teach these limitations or any equivalent of these limitations. Relying on Gardner v. TEC Systems,[24] the examiner argues that the limitation of the "...vessel having a draught of 10 meters- this pertains only to the size of the ship, which is not patentable." The foregoing implies that Gardner stands for the general proposition that recitation of the size of a claim element cannot render the claim patentable. Claim 16, however, is not limited to merely a ship having a particular draft, but recites among other things the particular draft in combination with a sea chest. As the examiner noted, the court in Gardner held that where the only difference between the prior art and the claimed subject matter was a recitation of relative dimensions of the claimed device and a device having the claimed relative dimensions would not perform differently than the prior art device, the claimed device was not patentably distinct from the prior art device.

In the present case, the cited dimensions relate to intake at a preferred depth with respect to a thermocline or plankton layer and are important for performance of the claimed desalination

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[22] The particular location of the water intake and concentrate discharge, the intake at below the thermocline region and discharge above, the concentrate discharge having a plurality of ports, a mixing space aboard the ship, a sea-going vessel having a draft of 10 meters, and a sea chest.
[23] 675 F. 2d 297 (CCPA 1982).
[24] 725 F.2d 1338 (Fed. Cir. 1984).

system. To illustrate, in a case where the plankton level is very near the surface of a body of water, a vessel with a draught of less than 3 meters and a sea chest intake would not likely be able to minimize plankton intake, whereas one with a draught of greater than 10 meters would. Thus, referring again to the Gardner case, the relevant dimension in this case could cause the vessel to perform differently.

Regarding claim 17, neither Lampe nor Bosley teach or suggest a "...water intake member extendible from the hull into the body of seawater, wherein the water intake is on the distal end of the water intake member and the first depth is greater than ten meters" or any equivalent thereof. The current office action failed to respond to this argument when it was presented in appellant's July 27, 2006 amendment and August 29, 2006 Arguments for the Pre-appeal Brief Conference Request.

Regarding claim 19, neither Lampe nor Bosley teach or suggest a discharge port at the indicated site. Moreover, in Bosley's device, discharge of concentrate at a depth shallower than the intake would appear to defeat the purpose of its mid-water discharge. The current office action also failed to respond to this argument when it was presented in appellant's July 27, 2006 amendment and August 29, 2006 arguments for the pre-appeal brief conference request.

Lampe and Bosley also fail to teach or suggest claim 20's "...wherein the at least one discharge port is positioned in or below a thermocline and the first depth is above the thermocline;" claim 21's "...wherein the at least one discharge port is positioned above a thermocline and the first depth is in or below the thermocline;" claim 22's "...wherein the water intake is movable such that the water intake system can intake water from various depths to reduce the intake of plankton;" or claim 23's "...wherein the first sea-going vessel comprises a sea chest formed in the lower portion of the hull of the first sea-going vessel and a water intake

member extendible from the hull into the body of seawater, and the water intake system can utilize either the sea chest or the water intake member to intake seawater." The current office action also failed to respond to these arguments when they were presented in appellant's July 27, 2006 amendment and August 29, 2006 arguments for the pre-appeal brief conference request.

As to claims 30, 31, 33-35, and 37-41 which depend from claim 28, for reasons similar to those presented above, appellant does not believe that any of these additional limitations are taught or suggested by Lampe or Bosley.

Each of the limitations in the foregoing dependent claims provides advantages to the subject desalination system depending on its particular application. None of these advantages are appreciated by Lampe or Bosley. Further, in contravention of rule 104, the examiner did not provide specific reasons for these rejections.

The Lampe and Permar combination fails to teach or suggest seawater intake at a first depth and concentrate discharge at a site other than the first depth

In the current office action, the examiner argued:

> Lampe teaches a system and a process of desalination using reverse osmosis as claimed, wherein the system is installed aboard a ship. However, Lampe does not teach the specifics of water intake and concentrate discharge.
>
> Permar teaches a desalination system for seawater having reverse osmosis membranes, in which the concentrate is diluted by mixing with seawater before discharge in a plenum (44) see abstract, column 1 lines 50-64, column 3 lines 23-40 and figure 1. It would be obvious to one of ordinary skill in the art at the time of the invention to use the teaching of Permar in the teaching of Lampe because Permar teaches a system which provides highly effective filtering with expenditure of considerably less energy and improved recovery from subsequent downstream filters in a series of filters, unlike the prior arts.

Although the examiner acknowledges that Lampe does not teach the specifics of water intake and concentrate discharge, he does not similarly acknowledge that Permar also fails to teach seawater intake at a first depth and concentrate discharge at a site other than the first depth. Nowhere in Permar is there mention of this limitation which is included in independent claims 15 and 28 from which the remainder of the claims rejected under this section depend. Furthermore, the individual additional limitations of each of the rejected dependent claims are also not taught or suggested by either Lampe or Permar. Accordingly, this rejection is in error.

The Lampe/Bosley/Permar combination fails to teach or suggest discharge of diluted concentrate

In the current office action, the examiner argued that:

> [i]t would have been obvious to one of ordinary skill in the art at the time of the invention to use the teaching of Bosley and Permar in the teaching of Lampe because Bosley teaches protecting the environment by diluting the concentrate at discharge; and Permar teaches diluting the concentrate in the system for improved performance, with concentrate discharged after dilution.

The foregoing argument is incorrect because Permar does not teach discharge of diluted concentrate. After carefully reviewing Permar (including the abstract, column 1 lines 50-64, column 3 lines 23-40 and figure 1 as noted by the examiner), appellant could not find a description of discharge of diluted concentrate. Rather, looking more closely at column 3 lines 23-40, Permar teaches dilution of concentrate prior to filtration – not discharge ("...seawater or other liquid is mixed with the recirculated concentrate prior to entering each of the reverse osmosis filters"). In Permar, the problem addressed relates specifically to a desalination system featuring a plurality of reverse osmosis filters in series. In such a system, seawater passes through the first filter with high efficiency yielding a permeate and a concentrate more saline

than seawater. The concentrate more saline than seawater is then passed through the second filter –but with less efficiency than with the first filter because the liquid being filtered is the concentrate (which is more saline than seawater). With each filter after the second, the filtering efficiency further decreases because the liquid being filtered becomes more and more saline. Permar proposes mitigating this problem by mixing the concentrate resulting from each filtering step with seawater prior to passing it through the subsequent downstream filters. In this way, each filter is more efficient because the liquid each filters is less saline than in the corresponding conventional configuration. Permar, however, does not describe discharge of diluted concentrate.

Because neither Lampe, Bosley, or Permar teach discharge of diluted concentrate, the combination of these references cannot teach all of the limitations of independent claims 15 and 28, nor any claim dependent thereon. Further, the combination of Lampe, Bosley, and Permar fail to teach the additional limitations recited in dependent claims 16, 17, 9-23, 31, 33-35, and 37-41. Accordingly, this rejection is in error.

VIII. Conclusion

Appellant has demonstrated that the present invention as claimed is clearly distinguishable over the art cited of record and the specification complies with all §112 requirements. Therefore, appellant respectfully requests the Board of Patent Appeals and Interferences to reverse all rejections and instruct the examiner to issue a notice of allowance of all claims.

The Commissioner is hereby authorized to charge the statutory fee of $250.00 as well as any underpayment or credit any overpayment of fees under 37 CFR 1.17 as required by this paper to Deposit Account 50-3110.

Respectfully submitted,

Date: December 7, 2006

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Claims Appendix

15. A system for desalinating seawater to yield desalinated water and a concentrate, the system comprising:

a first sea-going vessel comprising a hull and being positioned on the surface of a body of seawater;

a water desalination system installed on the first sea-going vessel, the water desalination system capable of removing salt from seawater;

a water intake system installed on the first sea-going vessel and comprising an apparatus for taking up seawater from the body of seawater, the apparatus comprising at least one water intake positioned in the body of seawater at a first depth;

a mixing system for mixing the concentrate with seawater to yield a diluted concentrate, the mixing system being installed on the first sea-going vessel in communication with the water desalination system and comprising a space in which concentrate can be mixed with seawater to form the diluted concentrate, an inlet for introducing concentrate into the space, an inlet for introducing seawater into the space, and an outlet for discharging the diluted concentrate from the space; and

a concentrate discharge system for discharging the diluted concentrate from the first sea-going vessel, the concentrate discharge system being installed on the first sea-going vessel and comprising at least one discharge port being positioned at a site not at the first depth.

16. The system of claim 15, wherein the first sea-going vessel has a draught of more than 10 meters and the apparatus for taking up seawater from the body of seawater comprises a sea chest formed in the lower portion of the hull of the first sea-going vessel.

17. The system of claim 15, wherein the apparatus for taking up seawater from the body of seawater comprises a water intake member extendible from the hull into the body of seawater, wherein the water intake is on the distal end of the water intake member and the first depth is greater than ten meters.

18. The system of claim 15, wherein the at least one discharge port is positioned at a site deeper than the first depth.

19. The system of claim 15, wherein the at least one discharge port is positioned at a site more shallow than the first depth.

20. The system of claim 15, wherein the at least one discharge port is positioned in or below a thermocline and the first depth is above the thermocline.

21. The system of claim 15, wherein the at least one discharge port is positioned above a thermocline and the first depth is in or below the thermocline.

22. The system of claim 15, wherein the water intake is movable such that the water intake system can intake water from various depths to reduce the intake of plankton.

23. The system of claim 15, wherein the first sea-going vessel comprises a sea chest formed in the lower portion of the hull of the first sea-going vessel and a water intake member extendible from the hull into the body of seawater, and the water intake system can utilize either the sea chest or the water intake member to intake seawater.

24. The system of claim 15, wherein the first sea-going vessel comprises instrumentation and sensors for detecting the presence of and depth of thermoclines in the body of seawater.

25. The system of claim 15, wherein the first sea-going vessel comprises instrumentation and sensors for detecting the presence of and depth of plankton in the body of seawater.

26. The system of claim 15, wherein the mixing system is integrated with the concentrate discharge system, and comprises a concentrate discharge member extending from the hull into the body of seawater, the concentrate discharge member comprising (a) a conduit through which concentrate can flow from the water desalination system to the body of seawater and (b) an aspirator through which seawater from the body of seawater can be drawn into the concentrate discharge member by the Venturi effect to mix with concentrate in the conduit.

27. A system for desalinating seawater to yield desalinated water and a concentrate, the system comprising:

a first sea-going vessel being positioned on the surface of a body of seawater;

a water desalination system installed on the first sea-going vessel and capable of removing salt from seawater to yield desalinated water and a concentrate;

a water intake system installed on the first sea-going vessel in fluid communication with the water desalination system and comprising an apparatus for taking up seawater from the body of seawater, the apparatus positioned in the body of seawater at a first depth relative to the surface of the body of seawater; and

a concentrate discharge system for discharging the concentrate from the first sea-going vessel, the concentrate discharge system being installed on the first sea-going vessel in fluid communication with the water desalination system and comprising at least one discharge member positionable in the body of seawater and comprising (a) a conduit through which concentrate can flow from the water desalination system to the body of seawater and (b) an aspirator through which seawater from the body of seawater can be drawn into the discharge member to mix with concentrate in the conduit.

28. A method of desalinating seawater on a sea-going vessel positioned on the surface of a body of seawater, the method comprising the steps of:

intaking seawater from the body of seawater at a first depth into the vessel;

removing salt from the seawater taken into the vessel to yield desalinated water and a concentrate;

diluting the concentrate with seawater to yield a diluted concentrate;

discharging the diluted concentrate into the body of seawater at a site not at the first depth.

30. The method of claim 28, wherein the step of diluting the concentrate with seawater occurs on the vessel.

31. The method of claim 28, wherein the body of seawater comprises a layer of phytoplankton and the first depth is below the layer of phytoplankton.

32. The method of claim 28, wherein the concentrate is discharged at a site deeper than the first depth.

33. The method of claim 28, wherein the concentrate is discharged at a site more shallow than the first depth.

34. The method of claim 28, wherein the concentrate is discharged at a site in or below a thermocline and the first depth is above the thermocline.

35. The method of claim 28, wherein the concentrate is discharged at a site above a thermocline and the first depth is in or below the thermocline.

37. The system of claim 15, wherein the first sea-going vessel comprises at least one selected from the group consisting of (i) a means for regulating the salinity level of the concentrate to a level substantially equal to the salinity level of the seawater at the area where the concentrate is discharged and (ii) a means for regulating the temperature of the concentrate substantially equal to the temperature of the seawater at the area where the concentrate is discharged.

38. The system of claim 37, wherein the first sea-going vessel comprises both (i) the means for regulating the salinity level of the concentrate to a level substantially equal to the salinity

level of the seawater at the area where the concentrate is discharged and (ii) the means for regulating the temperature of the concentrate substantially equal to the temperature of the seawater at the area where the concentrate is discharged.

39. The method of claim 28, wherein the diluted concentrate has a salinity level substantially equal to the salinity level of the seawater at the area where the concentrate is discharged.

40. The method of claim 28, wherein the diluted concentrate has a temperature substantially equal to the temperature of the seawater at the area where the concentrate is discharged.

41. The method of claim 28, wherein the diluted concentrate has a salinity level substantially equal to the salinity level of the body of seawater at the area where the concentrate is discharged and the diluted concentrate has a temperature substantially equal to the temperature of the seawater at the area where the concentrate is discharged.

References Appendix

Attached hereto are the following references:

US 5,834,641;

Ashjian et al., "Distribution of plankton, particles, and hydrographic features across Georges Bank described using the Video Plankton Recorder." Deep-Sea Research Part II-Topical Studies in Oceanography. 48 (1-3), 2001;

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Davis et al. "Microaggregations of Oceanic Plankton Observed by Towed Video Microscopy", Science 257, 1992; and

Flagg and Smith, "On the use of the Acoustic Doppler current profiler to measure zooplankton abundance," Deep Sea Res. 36, 1989.

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Deep-Sea Research II 48 (2001) 245–282

DEEP-SEA RESEARCH
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Distribution of plankton, particles, and hydrographic features across Georges Bank described using the Video Plankton Recorder☆

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Abstract

It is well known that plankton abundance is highly variable over a broad range of scales. Conventional sampling with nets, pumps, and bottles is discrete and covers only a small portion of the total variance spectrum. Development of the Video Plankton Recorder (VPR) has enabled us to quantify the abundance of seston and plankton, including delicate taxa, over a range of scales from centimeters to hundreds of kilometers. During the 1994–1995 GLOBEC Georges Bank field years, three VPR surveys were conducted across the bank from the Slope Water in the south to the Gulf of Maine in the north, a distance of ~ 200 km. The surveys, conducted in June 1994, January 1995, and March 1995, intersected at least four distinct water types (Slope Water, stratified bank water, well-mixed bank water, Gulf of Maine water) and crossed several frontal boundaries (shelf break front, tidal front, Gulf of Maine front). The Video Plankton Recorder was equipped with temperature, conductivity, fluorescence, and transmissivity probes in addition to two video cameras, permitting comparison of the plankton and particle distributions with the physical fields. Only data collected using the low-magnification camera are considered here. A combination of analytical methods including temperature–salinity–plankton plots and statistical analyses (spatial variance spectra, principle component analysis, and correlation analysis) revealed that the distribution of taxa and particles were associated with particular water mass types but that smaller-scale variability in plankton abundance did not appear to be tightly coupled to or correlated with hydrography. The distributions and seasonal progression in abundance of *Calanus finmarchicus*, the most abundant plankton taxon, revealed a deep dwelling population in the Slope Water and shallower populations on the bank and in the Gulf of Maine in January with abundance becoming increasingly greater on the bank in March and June. The data indicate that physical advection of water mass types and intrinsic plankton was important to the establishment of *Calanus* populations on Georges Bank.

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1. Introduction

Both physical and biological processes produce the distributions of plankton and particles observed on Georges Bank. Physical mechanisms such as advection, frontal isolation, tides, and the establishment of stratification determine water mass and plankton distribution, modify environmental conditions in various regions of the bank, and influence the input, retention, or loss of water and populations from the bank (immigration and emigration). Biological processes such as growth, reproduction, and mortality act within the physical environment to further modify abundances and distributions. One of the goals of the US GLOBEC Georges Bank research program is to identify and describe these biophysical mechanisms and their impact on zooplankton populations in this region (GLOBEC, 1992).

Georges Bank is characterized by complex circulation and hydrography (e.g., Hopkins and Garfield, 1981; Flagg, 1987; Butman et al., 1987), with characteristic water types present at different geographic locations. Georges Bank Water on the crest of the bank is separated from Gulf of Maine Water to the north and Shelf Water on the southern flank of the bank by tidal mixing fronts (northern and southern tidal mixing fronts). The Shelf Water and Slope Water found along the southern edge of the bank are separated by the prominent Shelf–Slope Front. Both Gulf of Maine Surface Water and Shelf Water are modified seasonally by increased insolation during the spring and summer, which leads to the development of stratification. In contrast, Georges Bank Water on the crest remains well-mixed throughout the year. These seasonally varying conditions of vertical structure also modify the strength of the density structure of the tidal mixing fronts, particularly along the southern edge of the crest, such that the southern tidal mixing front may not be distinct in hydrographic data during the winter when little contrast in vertical structure exists between the Shelf Water and Georges Bank Water. Episodic events such as storms, interactions with Gulf Stream rings, or anticyclonic eddies in the Slope Water transport water masses and plankton populations onto or off of Georges Bank (e.g., Ramp et al., 1983; Churchill et al., 1986; Houghton et al., 1986; Flagg, 1987; Garvine et al., 1988; Garfield and Evans, 1989; Lewis et al., 1994) Injections of Scotian Shelf Water also occur on the eastern end of the bank onto the southern flank (e.g., Bisagni et al., 1996).

The mean circulation on Georges Bank is dominated by anticyclonic flow around the margins of the crest outside of the tidal mixing fronts (e.g., Bumpus, 1976; Butman et al., 1987; Limeburner and Beardsley, 1996). This flow is narrowly focused along the northern flank of the bank but more diffuse across the southern flank. The strength of the current varies seasonally, with more intense flow and higher velocities occurring following the development of density stratification during spring and summer. The system becomes a partially closed gyre during late spring and summer, with recirculation occurring from the southern flank to the northern edge along the western end of the bank (e.g., Butman and Beardsley, 1987; Limeburner and Beardsley, 1996). The observed currents on the bank are impacted strongly by tidal currents, which may obscure the prevailing anticyclonic circulation if such data are uncorrected for the tidal signal (e.g., Moody et al., 1983; Candela et al., 1992).

These variable hydrographic and circulation patterns, in conjunction with individual life histories, are important to the distribution of plankton populations across the bank since advection and the modification of the physical environment (e.g., development of stratification) are critical towards determining the ultimate distribution of a taxon. The general seasonal cycle of

zooplankton taxa across Georges Bank has been described (e.g., Bigelow, 1926; Davis, 1987). The copepod *Calanus finmarchicus* (and congeneric species; herein "*Calanus*") in particular has received considerable attention as it can be a dominant component of the total zooplankton biomass during winter and spring (e.g., Bigelow, 1926; Davis, 1987; Meise and O'Reilly, 1996) and its young are believed to be a significant food source for larval cod and haddock (Kane, 1984; Buckley and Lough, 1987). Abundances and distributions of *Calanus* on the bank vary throughout the year. *Calanus finmarchicus* establishes strong populations on Georges Bank during January 1995, developing to a biomass peak in late spring (May–June; Davis, 1987; Meise and O'Reilly, 1996). Abundances on the bank diminish during the warm summer months, and populations must be reestablished during the following winter through recolonization (e.g., Davis, 1987; Meise and O'Reilly, 1996). It is believed that populations on the bank originate in the Gulf of Maine to the north and are advected onto the bank at the northeast corner (Northeast Peak) (e.g., Meise and O'Reilly, 1996; Durbin et al., 1997, unpublished data; Hannah et al., 1998). Advection subsequently spreads populations of the copepod along the southern flank and to the southwestern corner of the bank; some retention on the bank may occur in recirculation along the southwestern edge (e.g., Limeburner and Beardsley, 1996; Manning and Beardsley, 1996; Durbin et al., 1997, unpublished data). Because of its importance to the ecosystem, including as a food source for larval cod and haddock, this species was selected as one of the target species for the US GLOBEC Georges Bank program (GLOBEC, 1992).

The present study quantified the distributions of plankton and particles (e.g., marine snow) and the associations of these distributions with the physical environment (temperature, salinity, velocity) from transects across Georges Bank conducted in three different months during 1994 and 1995 as part of the GLOBEC Georges Bank Program. The transects were surveyed using the Video Plankton Recorder (VPR; Davis et al., 1992a), which produces high-resolution descriptions of plankton distributions. The VPR describes plankton abundances and community compositions that are similar to those observed using conventional net systems, such as the multiple opening/closing net and environmental sensing system (MOCNESS; Wiebe et al., 1976, 1985) for abundant taxa, although the VPR may not differentiate different species or different life stages within a species (e.g., Benfield et al., 1996). For regions with a low diversity of copepods, such as Georges Bank, the instrument is able to differentiate between certain copepod genera and species. The VPR is more effective than conventional net systems at describing the abundances and distributions of fragile, gelatinous taxa since the instrument samples non-invasively (e.g., Davis et al., 1992b; Benfield et al., 1996; Gallager et al., 1996; Norrbin et al., 1996). Furthermore, far greater spatial resolution (< 1 m) of both biological and physical fields is achieved using the VPR than with conventional net systems (e.g., Davis et al., 1992b; Gallager et al., 1996).

The specific goals of the study were to (1) describe the distributions of dominant plankton taxa and particles across Georges Bank, (2) identify associations between the plankton distributions and hydrographic characteristics and water masses, (3) document changes in these distributions and associations throughout the winter–spring period, (4) describe the dominant spatial scales of patchiness of the dominant plankton and physical mechanisms that impact such patchiness, and (5) identify potential avenues of on-bank or off-bank flux of plankton populations.

2. Methods

Three 180–200 km long transects across the northeast region of Georges Bank were conducted during 15–16 June, 1994 (R/V Columbus Iselin) and 18–19 January, 1995 and 6–8 March, 1995 (R/V Endeavor). Each transect extended from the Slope Water south of Georges Bank to the Gulf of Maine (Fig. 1). The two transects conducted in 1995 followed a straight line while the 1994 transect contained a turn near the midpoint. The transects conducted in 1995 also were accomplished in two segments, with some time interval (16 h, January 1995; 25 h, March 1995;) between each leg. As a result, time is not continuous across these transects. The Video Plankton Recorder (VPR) was towed at 2 m/s (~ 4 knots), undulating continuously from surface to near bottom (towyo) (Fig. 2). For these surveys, the VPR was equipped with 2–4 cameras, temperature and conductivity probes, fluorometer, and transmissometer. The present study examines the distributions of plankton obtained from the camera with a field of view of ~ 37 × 24 × 40 mm (W × H × D) (the actual field of view and volume imaged differed slightly (~ 1 mm) for each cruise), producing an imaged volume of ~ 35 ml. This magnification is suitable for imaging copepods of 1–2 mm prosome length, such as late copepodites of *Calanus finmarchicus*, but not for identifying naupliar stages, early copepodites, or for effectively enumerating the abundances of very small copepods such as *Oithona* spp. Environmental data were collected at 0.25 Hz (June 1994) or 0.5 Hz (January 1995, March 1995) Hz; video images were recorded at 60 fields per second (fps).

Video tapes were analyzed for plankton abundances using a semi-automated method (Davis et al., 1996). In-focus images were extracted from the video tapes and saved to disk as tiff files using an Imaging Technologies Series 151 Image Processor and a Sun Sparc 20 workstation. The images were identified by hand to particle type, taxon, or species and measured using a custom routine

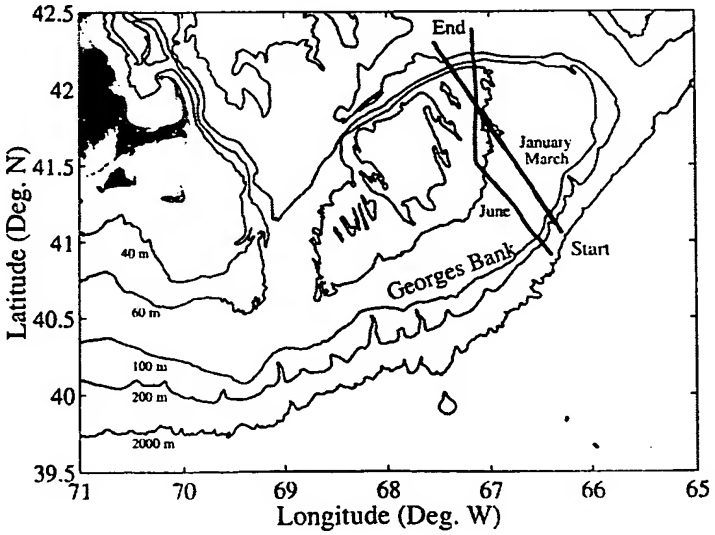

Fig. 1. Location of three cross-bank transects. The June 1994 (CI9407) transect was conducted on the R/V Columbus Iselin and the January 1995 (EN259) and March 1995 (EN262), transects were conducted on the R/V Endeavor. Note that the transects from 1995 followed a straight course across the bank while the 1994 transect consisted of two legs.

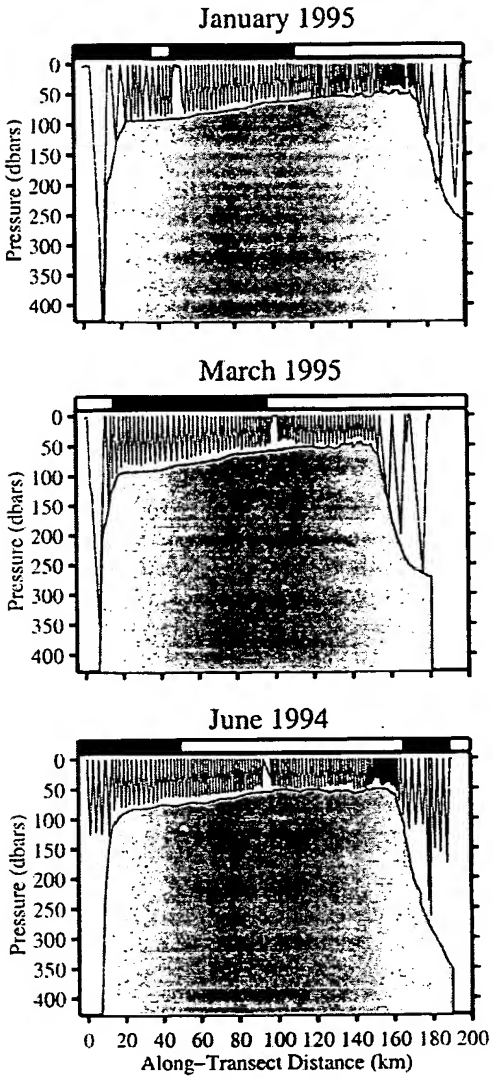

Fig. 2. Towyo path of the instrument through the water as a function of along-transect distance. Along transect distance for the three transects was calculated from the geographic starting location of each transect, rather than a common starting point. The instrument was deployed to approximately 10 m off of the bottom during most towyos. Periods of night (black) and day (white) indicated across the top of each graph.

written in MATLAB (Mathworks, Inc.; see Davis et al., 1996). The size measurement of each particle or organism was obtained by manually identifying two locations on each image; for copepods, the width of each individual was measured (the animals were rarely oriented parallel to the field of view and hence an accurate length measurement could not be obtained). The number of images extracted and examined (28,906, 72,262, and 41,681 for January 1995, March 1995, and June 1994, respectively) were somewhat greater than the numbers identified (14,401, 38,575, 29,462) as

some portion of the extracted images were not in focus and hence not within the imaged volume. Twenty taxa, species, or particle types were identified routinely; only the most abundant are discussed here. Life stage was not differentiated for the copepods. Plankton and particle observations were merged with environmental and navigational data by binning the observations for each category into the time intervals at which the environmental data were collected using routines written in MATLAB (see Davis et al., 1996); concentrations were calculated utilizing the total volume (liters) imaged during that period. For less-abundant categories, usually only a single organism was observed during each time interval so that the resulting concentrations are close to presence or absence data rather than covering a range of values.

Although data were collected during three separate months, it is important to note that the June data were collected during 1994, a year prior to January 1995 or March 1995 data. In the present study, we consider the months in the temporal sequence of January 1995, March 1995, and June 1994 in order to examine seasonal patterns although the months were not surveyed chronologically. We describe features typical of the physical and biological distributions and mechanisms on Georges Bank for each month.

Principal component analysis was utilized to identify potential associations between hydrography, fluorescence, particulate concentration (represented by light attenuation), the abundance of *Calanus finmarchicus* (the most abundant taxon), and the concentration of marine snow and to describe the mesoscale spatial distribution of variability in these fields (e.g., Mariano et al., 1996). For these analyses, data first were standardized to the standard deviation of each variable, producing variances of 1.0 in the standardized data, prior to calculation of the eigenvalues and the variable mean was subtracted from each observation prior to calculation of the principal components. For the June 1994 data, the temperature and salinity data from the southern end of the transect were quite noisy, either because of the presence of very warm, salty Gulf Stream water that had been advected to the bank edge or because of spurious readings by the temperature or conductivity sensors. Hence, observation times with a temperature greater than 13°C were excluded from the principal component analysis. Correlation coefficients also were calculated between these variables in order to identify co-varying characteristics on a point-by-point basis. Because of the very high sample size (> 23,553 or greater), most correlation coefficients calculated were "significant" ($r_{0.05(2),1000} = 0.062$) and the correlation coefficients were utilized to identify data pairs for which a high proportion of the observed variation was correlated (Zar, 1984). The highly discrete distributions (presence/absence) of the less-abundant taxa were not appropriate for both analyses (principal component analysis, correlation) and meaningful results could not be obtained.

Velocities measured using an acoustic Doppler current profiler (150 kHz) were collected during the January 1995 cruise on the R/V Endeavor and were archived into a database at Brookhaven National Laboratory (C.N. Flagg, pers. comm.) (Acoustic Doppler current profiler data were not available from the March 1995 and June 1994 cruises). These data were used to explore the potential advection or flux of *Calanus* around and on or off of the bank. Acoustic Doppler current profiler velocities first were detided to remove the signature of the tidal ellipse from the data (Candela et al., 1992 and pers. comm.). Flux estimates were calculated by binning the *Calanus* abundance data to the time-depth bins of the ADCP vectors, multiplying each component of velocity by the average *Calanus* concentration for that depth and time bin, and resolving the components into a flux vector.

Power spectra for temperature, salinity, density, fluorescence, and the abundance of *Calanus* were computed to compare the scales of variability between the plankter and conservative properties (e.g., Platt and Denman, 1978). For reference, the spectrum for pressure also was computed. The 0.25 or 0.5 Hz data first were binned into 1-min intervals. The data then were normalized by subtracting the mean and dividing by the standard deviation. The MATLAB routine PSD then was used to compute the power spectrum density.

3. Results

3.1. Water masses and physical distributions

The different water masses present across the transect were identified using T/S plots (Fig. 3). Comparisons of the T/S plots from the different months revealed seasonal changes in water mass properties. The T/S diagrams for January 1995 and March 1995 were similar while that of June 1994 was distinctly different because of the establishment of stratification along the Georges Bank southern flank and in the Gulf of Maine. Both Upper (14°C, 35) Slope Water and Lower (4–6°C, 35) Slope Water were observed south of the bank (blue) during all three months (e.g., Flagg, 1987). Note that little or no Lower Slope Water was observed in the March 1995 and June 1994 data, in part because the sampling did not extend to depths greater than 350 m (March 1995) or 125 m (June 1994). Upper Slope Water was continuous with Shelf Water along a mixing curve gradient of temperature (6–14°C) and salinity (33–35); this mixture of water masses was found south of and in the Shelf-Slope Front. The exceptionally high salinity and temperature (14.5°C, 35.8) observed in the Slope Water during March 1995 and the considerable variability seen during June 1994 in the Slope Water probably resulted from interaction of near-bank waters with a Gulf Stream Ring or meander. Water along the southern flank (green) exhibited a narrow range of temperature/salinity characteristics during both January 1995 and March 1995. The T/S minimum at 4°C, 32.25 observed during March 1995 may have resulted from an influx of Scotian Shelf Water onto Georges Bank from across the Northeast Channel (e.g., Bisagni et al., 1996; D. Mountain, pers. comm. and unpublished data). Water across both the southern flank and the crest of the bank (yellow) was colder during March 1995, following winter heat loss and cooling, than during January 1995. Water on the crest of the bank, between the northern and southern tidal mixing fronts (yellow), exhibited almost constant temperature and salinity along a transect (7°C, 33.2, January 1995; 4–6°C, 32.5–33, March 1995; 9.5°C, 32.6, June 1994), as is characteristic of a well-mixed water mass (Georges Bank Water) (e.g., Hopkins and Garfield, 1981; Flagg, 1987). North of the northern tidal mixing front (red), both Intermediate (6–8°C, 33.5) and Bottom (8°C, 35) Maine Water were observed during all three months. Note that the properties of Maine Bottom Water and Lower Slope Water converge; it is thought that Maine Bottom Water along the northern edge of the bank may originate from Slope Water that enters the Gulf of Maine through the Northeast Channel (as Deep Channel Water) (Ramp et al., 1986; Loder et al., 1997; Smith et al., 2001). This may have important consequences to the distribution of plankton species, since deeper living species may be input to the Gulf of Maine from the Slope Water. The June 1994 T/S diagram is complicated by the establishment of stratification following heating and the subsequent development of surface water including Maine

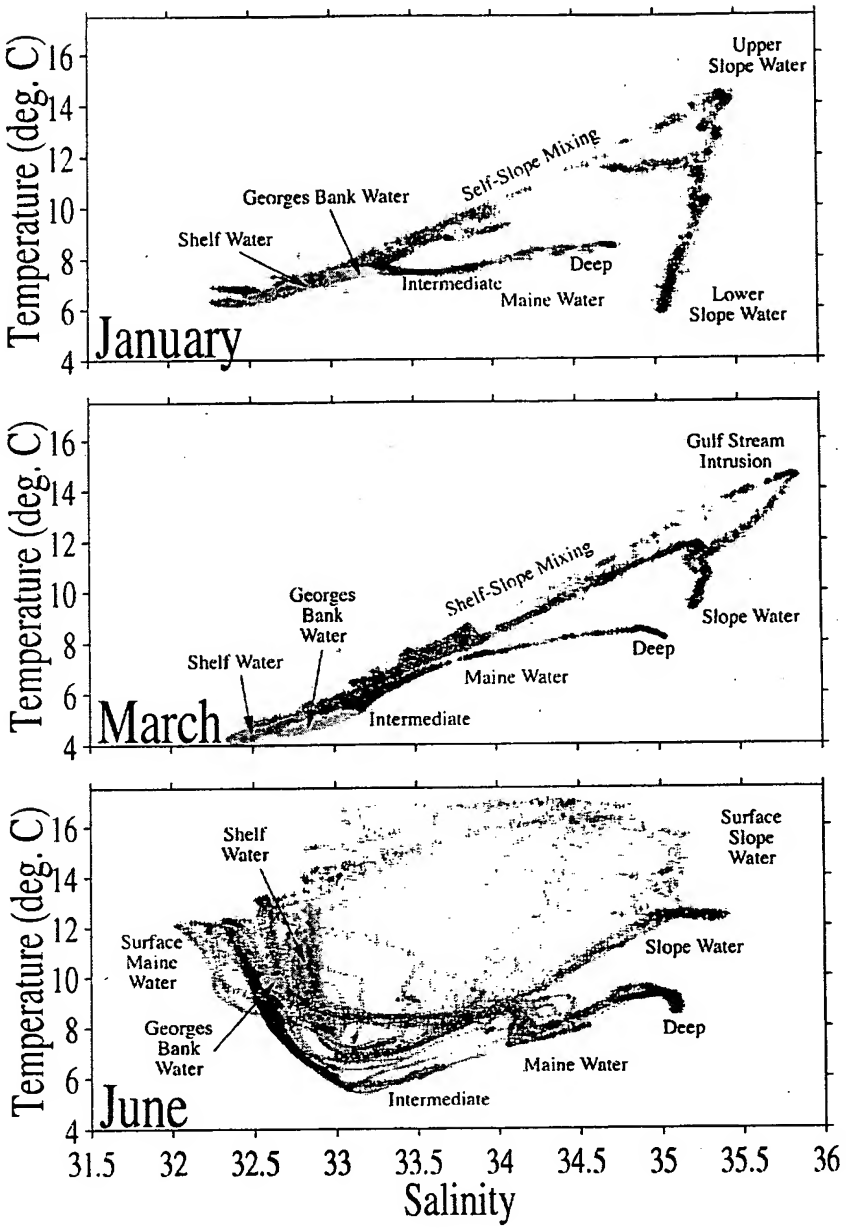

Fig. 3. Temperature/salinity diagrams for all three transects. Data collected in different geographic regions of the bank are plotted with the different colors (blue: south of the bank/Slope, green: southern flank, yellow; bank crest; red: north of the bank/Gulf of Maine). The cross-transect distances demarking the four regions differed slightly for each cruise (Slope: $\leqslant$ 30, 40, 30 km; Southern Flank: $>$ 30, 40, 30 and $\leqslant$ 100, 100, 80 km; Crest: $>$ 100, 100, 80 and $\leqslant$ 170, 150, 155 km; north/Gulf of Maine: $>$ 170, 150, 155 km for January 1995, March 1995, and June 1994, respectively). The characteristic water masses are identified on the diagrams.

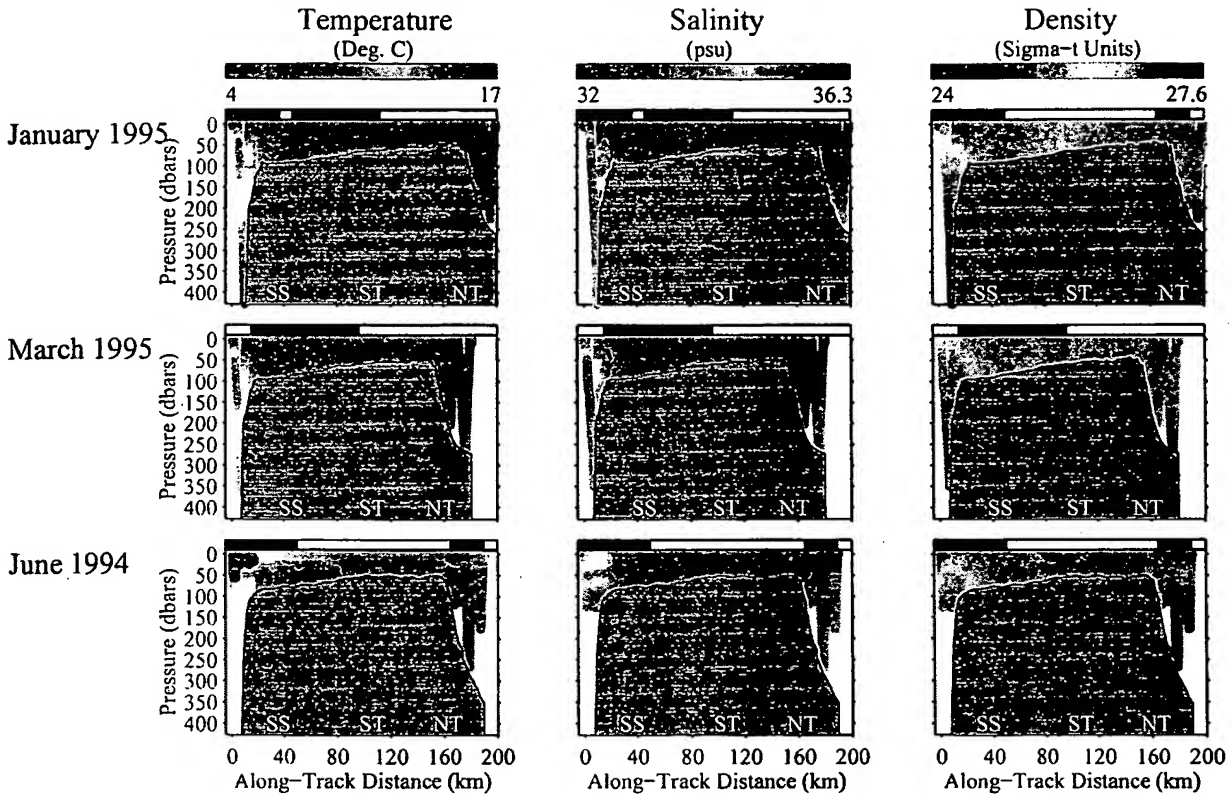

Fig. 4. Temperature (°C), salinity, and density (sigma-t) sections across the bank for all three transects. The distance–depth location of each observation is plotted as a dot, with the color of the symbol representing the magnitude each variable for that location. Note that transects do not start at a common geographic location. The approximate cross-transect locations of the Shelf–Slope (SS), southern tidal (ST), and northern tidal (NT) fronts are indicated. Periods of night (black) and day (white) indicated across the top of each graph. (n = 39,377, January 1995; n = 42,658, March 1995; 23,553, June 1994).

Surface Water (12°C, 32.5), Shelf Stratified Water (12.5°C, 33), and Surface Slope Water (14–16°C, 32.5–35.5).

The cross-bank distributions of temperature, salinity, and density (Fig. 4) demonstrated patterns and hydrographic features typical of Georges Bank for each season. In January 1995, both temperature and salinity were fairly uniform across the bank and into upper water column of the Gulf of Maine, with warmer and saltier water observed both in the deeper Gulf of Maine and in the deeper Slope Water. The northern flank tidal front was located at ~ 170 km along-transect distance and a water depth of ~ 50 m. To the south, the Shelf–Slope front was distinct at 30 km along-transect distance, with isoclines extending almost horizontally off of the bank over the Slope Water. As a result, Shelf Water from the southern flank extended off of the bank over the Slope Water. The southern flank tidal mixing front was located at ~ 100 km and a water depth of 50 m (see fluorescence and light attenuation); this feature was not obvious in the temperature and salinity

Table 1
Correlation coefficients between the hydrographic variables, fluorescence, attenuation, and concentration of *Calanus finmarchicus* for the three transects

	Temperature	Salinity	Sigma-*t*	Fluorescence	Attenuation	*C. finmarchicus*
January 1995 (n = 39,377)						
Temperature	1.00	0.73	0.45	−0.34	−0.38	−0.30
Salinity		1.00	0.94	−0.46	−0.42	−0.03
Sigma-*t*			1.00	−0.43	−0.36	0.06
Fluorescence				1.00	0.83	−0.07
Attenuation					1.00	−0.05
C. finmarchicus						1.00
March 1995 (n = 42,658)						
Temperature	1.00	0.97	0.87	−0.25	−0.20	−0.08
Salinity		1.00	0.97	−0.30	−0.21	−0.06
Sigma-*t*			1.00	−0.30	−0.18	−0.05
Fluorescence				1.00	0.86	−0.01
Attenuation					1.00	0.00
C. finmarchicus						1.00
June 1994 (n = 23,553)						
Temperature	1.00	0.14	−0.36	0.03	0.09	0.02
Salinity		1.00	0.87	−0.34	−0.65	−0.06
Sigma-*t*			1.00	−0.33	−0.65	−0.07
Fluorescence				1.00	0.62	−0.09
Attenuation					1.00	−0.02
C. finmarchicus						1.00

distributions. Density was closely correlated to salinity (corr. coef. = 0.94) but less so to temperature (corr. coef. 0.73) (Table 1).

By March 1995, water over Georges Bank had cooled and freshened relative to temperatures in January 1995. The northern tidal front was located at ~150 km along-track distance, where the water depth was ~55 m. The location of the southern tidal front was difficult to identify in the temperature and salinity distributions but should be located at ~100 km distance and ~50 m water depth. Note also that the southern tidal mixing front was crossed during the transition from night to day. The Shelf–Slope front was distinct at ~40 km along track distance. In contrast to January 1995, the Shelf–Slope front was more vertical, hence Shelf Water was confined to the shallow bank (< 100 m). Because the Shelf-Slope front did not extend off of the bank, the upper 50 m at the southern end of the transect comprised a mixture both of Shelf Water and Slope Water. Inshore of the front, Scotian Shelf Water influx was present as a shallow (25 m deep), pool of cold, fresh water extended from 20–50 km along track distance. Similar features were observed in the distribution of density, which was correlated both with salinity and temperature (corr. coef. 0.97 and 0.87); temperature and salinity likewise were correlated highly (corr. coef. 0.97) (Table 1).

The hydrography of Georges Bank in late spring/summer, here demonstrated by the June 1994 physical distributions, was quite different from winter conditions. With increased insolation,

stratification developed on the flanks of the bank and in the Gulf of Maine. The central bank remained well-mixed, with temperatures elevated relative to January 1995 and March 1995. The Shelf-Slope Front was located at ~ 30 km along track distance with a sharp boundary in both salinity and temperature. The southern tidal mixing front was located at ~ 80 km along track distance and was distinct especially in the temperature and density sections. Thermal stratification had developed in the Shelf Water to the south of the southern tidal mixing front. The northern tidal mixing front again was located at ~ 50 m water depth and at ~ 155 km along track distance; this front was crossed just prior to the transition from day to night. The "cold pool" in the lower half of the water column on the southern flank (~ 40 km along track distance) was a distinctive feature of the June transect. Cold bottom water also was observed on the northern edge of the bank. Density was well correlated with salinity (corr. coef. 0.87) but not correlated with temperature (− 0.36), indicating that density at this time was dependent primarily on salinity. The low correlation between temperature and salinity was evidence of thermal modification of the water masses that resulted from the increased insolation.

3.2. *Fluorescence and light attenuation*

Fluorescence (Fig. 5) was low during January 1995, with lowest values in the Gulf of Maine and Slope Water and slightly greater over the crest of the bank in Georges Bank Water. By March 1995, fluorescence had increased both on the crest of the bank (Georges Bank Water) and in and to the north of the Shelf–Slope Front, with greatest fluorescence at the southern end of the transect in the Shelf–Slope Front. The units in which fluorescence was measured during the June 1994 transect differed from those of the 1995 transects, so that only the relative distributions but not the absolute magnitudes of fluorescence between the three transects may be compared. Fluorescence in June 1994 was concentrated in and to the south of the northern tidal mixing front in Georges Bank Water and in stratified Shelf Water to the north of the Shelf–Slope front. Low levels of fluorescence were observed in and to the south of the southern tidal mixing front, both in well-mixed Georges Bank Water and in stratified Shelf Water. Little correlation between fluorescence and hydrographic characteristics (T, S) was observed (Table 1).

The distribution of particulate matter, represented here by light attenuation, exhibited many features similar to those of fluorescence in both January 1995 and March 1995, with lowest values in January 1995 and increased light attenuation in March 1995 (Fig. 5). Peaks in the concentration of particulate matter were seen during March 1995 at the Shelf–Slope Front and in Georges Bank Water to the south of the northern tidal mixing front. Elevated light attenuation also was observed in Maine Bottom Water, probably because of material resuspended off the bottom. Light attenuation was highly correlated with fluorescence for both January 1995 and March 1995 (0.83 and 0.86, respectively; Table 1). The distribution of light attenuation differed from that of fluorescence in June 1994, although some features were similar between the two. High light attenuation was observed in the well-mixed zone over Georges Bank, perhaps as a result of the resuspension of particulate matter at that location. This region of high particulate load extended to the south into the Shelf Water and through the upper layers of the Shelf–Slope Front. Some correlation between fluorescence and light attenuation was observed (0.616) during June 1994 (Table 1). Interestingly, light attenuation exhibited also some correlation with salinity/density during June 1994.

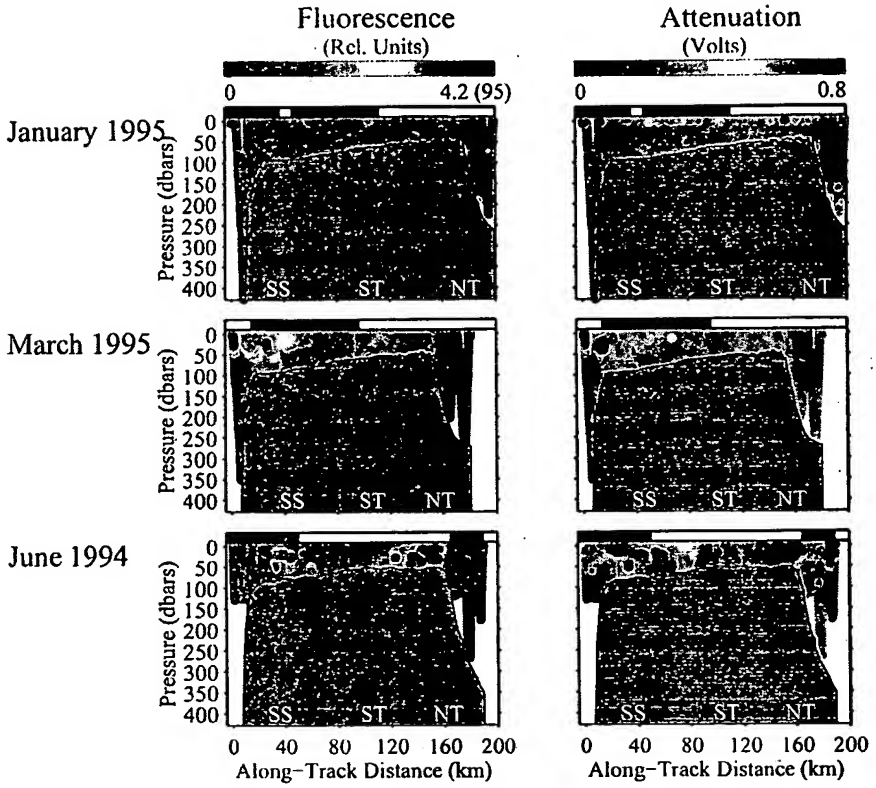

Fig. 5. Fluorescence (relative units) and light attenuation (V) sections across the bank for all three transects. The distance-depth location of each observation is plotted as a dot, with the color of the symbol representing the magnitude each variable for that location. Fluorescence ranged from 0–4.2 relative units for the January 1995 and March 1995 cruises and from 0–95 relative units for the June 1994 cruise. Note that transects do not start at a common geographic location. The approximate cross-transect locations of the Shelf–Slope (SS), southern tidal (ST), and northern tidal (NT) fronts are indicated. Periods of night (black) and day (white) indicated across the top of each graph.

3.3. *Distributions of abundant plankton and particles*

3.3.1. *Calanus finmarchicus*

Calanus finmarchicus, one of the GLOBEC Georges Bank target species, was numerous over the bank (Fig. 6), with marked changes in distribution at the different sampling times. Because of its abundance on Georges Bank and because of the relatively low diversity of copepod species on Georges Bank, it was possible to identify *C. finmarchicus* to species but not to stage within the species. Hence, references to "*Calanus*" throughout refer to individuals identified as being *Calanus finmarchicus* with no identification of life stage, although based on the magnification of the camera utilized we expect that most were late-stage copepodites. *Calanus* were significantly larger during March 1995 (1.10 ± 0.27 mm) and June 1994 (1.1 ± 0.21 mm) than during January 1995 (0.98 ± 0.2 mm), based on body width measurements (mean $\pm$ standard deviation; ANOVA, $p < 0.001$; Student–Newman–Keuls post-hoc test, $p < 0.001$; Zar, 1984); this may be because of

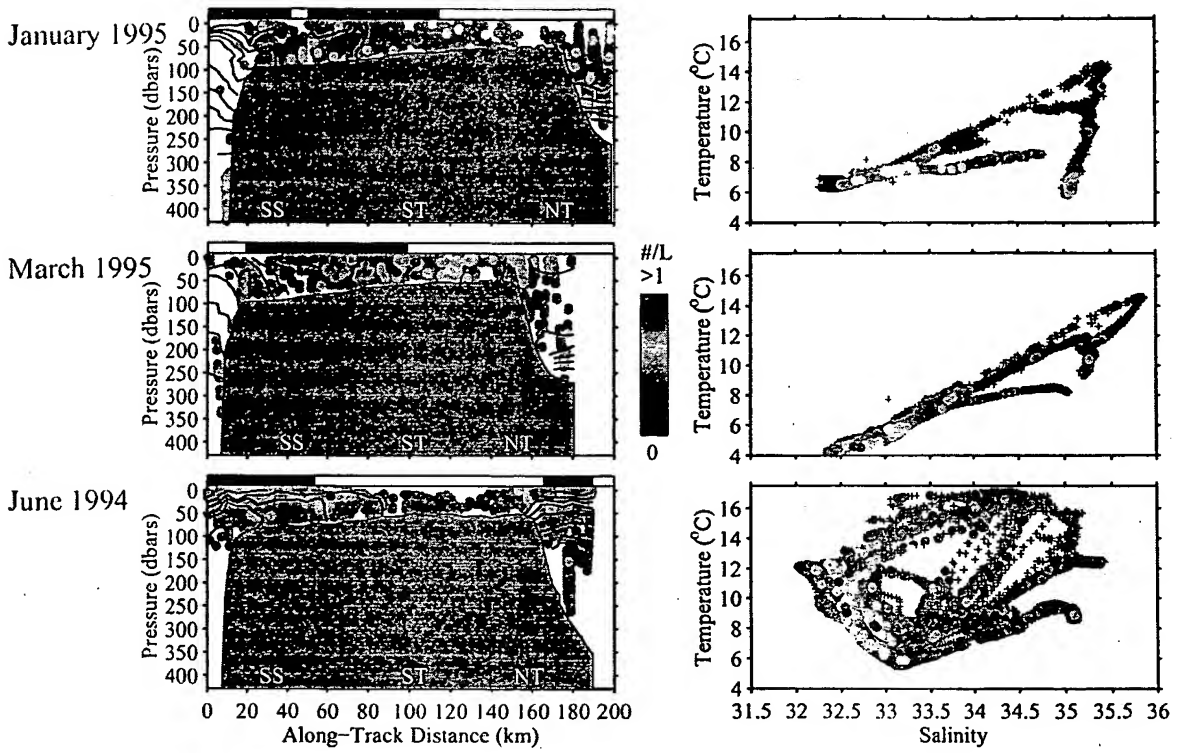

Fig. 6. Distribution of the copepod *Calanus finmarchicus* across the three transects (left) and as a function of temperature and salinity (right). The distance–depth or temperature–salinity location of each observation is plotted as a dot, with the color of the symbol representing the concentration (#/L) for that location. For the cross-transect distributions, note that transects do not start at a common geographic location. The approximate cross-transect locations of the Shelf-Slope (SS), southern tidal (ST), and northern tidal (NT) fronts are indicated. Periods of night (black) and day (white) indicated across the top of each transect graph. Contours of density also are shown (black lines). For the temperature–salinity–plankton diagrams, all *t–s* pairs are plotted as black crosses in addition to the *t–s* locations where *Calanus* were observed.

greater food availability (phytoplankton, microzooplankton) during late spring and summer, which increased the size of the animals. The association of *Calanus* with specific water types was demonstrated clearly through plots of *Calanus* abundance as a function of salinity and temperature (TSP Plots; e.g., Gallager et al., 1996) (Fig. 6). During January 1995, *Calanus* was present in low abundances in all water types except for Upper Slope Water. Greatest abundance was seen in the Lower Slope Water to the south of the bank (6°C, 35). By March 1995, abundances were elevated relative to January 1995, especially on the crest of the bank between the two tidal mixing fronts and in the upper Gulf of Maine water to the north of the northern tidal mixing front. The absence of *Calanus* from the very warm, salty Gulf Stream–Slope Water mix (> 12°C, > 35.5) found at 50–100 m at the southern end of the transect was conspicuous. *Calanus* also were not particularly abundant in the Scotian Shelf Water influx, although high abundances were seen in very cold and fresh water at other locations. *Calanus* were most abundant in June 1994. However, abundances over the crest of the bank were much diminished relative to those observed in both January 1995

and March 1995. Greatest abundances were observed in the stratified water both of the southern flank and of the Gulf of Maine located just to the north of the northern tidal mixing front. Despite the obvious association of *Calanus* with particular water mass types observed in the TSP plots, no correlations between *Calanus* abundance and any physical variable, fluorescence, attenuation, or marine snow were observed (Table 1). Vertically, *Calanus* were most abundant in the thermocline between the warm surface water and the cooler deep water, as seen both in the vertical distribution and by the high abundances of *Calanus* found in the vertical mixing portion of the shelf water and Gulf of Maine water in the T/S plot. For all three months, there was no noticeable diel change in vertical distribution at any of the seven day–night transitions based on visual inspection of the distributions (and see below), despite the coincidence or proximity of the day–night transition with the time of crossing at two of the fronts (March 1995, June 1994).

The vertical distributions of both *Calanus* and fluorescence across the transects were further examined through consideration of the weighted mean depth of the vertical distributions and the normalized weighted mean depth (e.g., Roe et al., 1984; Durbin et al., 1997). For these calculations, data were averaged into 5 km along-transect distance × 5 m depth bins. The mean depth for each along-track distance was calculated as

$$\sum_{i=1}^{49} n_i z_i \, \mathrm{d}z \Big/ \sum_{i=1}^{49} n_i \, \mathrm{d}z,$$

where z_i is the mid-depth of each 5 m ith depth bin, n_i is the concentration of *Calanus* or the fluorescence at that ith depth, and $\mathrm{d}z$ the depth interval between bins (5 m). Visual comparison of the weighted mean depths (Fig. 7) with the vertical sections of *Calanus* abundance (Fig. 6) demonstrated that the weighted mean depth was an accurate representation of the vertical distribution of the species, although the weighted mean depth usually was found below the abundance maximum at a particular location. For most cross-transect locations, *Calanus* were distributed homogeneously throughout the water column or concentrated in a single portion of the water column (Fig. 6), with few if any locations demonstrating a bimodal distribution. Hence, the weighted mean depth represents the central tendency of the depth distribution. The weighted mean depths were normalized to the maximum depth sampled at each 5 km along-track distance bin by dividing the mean depth by the maximum depth, obtaining values ranging from 0–1.0, which indicated the mean depth of *Calanus* relative to the total water column at that location (normalized weighted mean depth; Fig. 7). The normalized weighted mean depths indicate whether the animals or fluorescence (1) were distributed homogeneously throughout the water column or concentrated at the mid-depth (0.5) or (2) were concentrated in the upper (< 0.5) or lower (> 0.5) portions of the water column. A t-test was employed to ascertain whether the normalized weighted mean depths within a region were significantly different from 0.5 (Zar, 1984).

Calanus were found at greatest depths in the Slope Water to the south of the bank and in the Gulf of Maine to the north (Fig. 7, left panels; note that Lower Slope Water was not sampled in June 1994). Little variation in weighted mean depth was seen across the southern flank and Crest of the bank along any of the transects. The weighted mean depths of fluorescence were similar to those of *Calanus* across the southern flank and Crest of the bank during January 1995 but deeper in the water column during March 1995 on the Crest and during June 1994 on the southern flank ($p < 0.05$; Wilcoxon Signed Rank Test). Fluorescence had a shoaler distribution than *Calanus* in

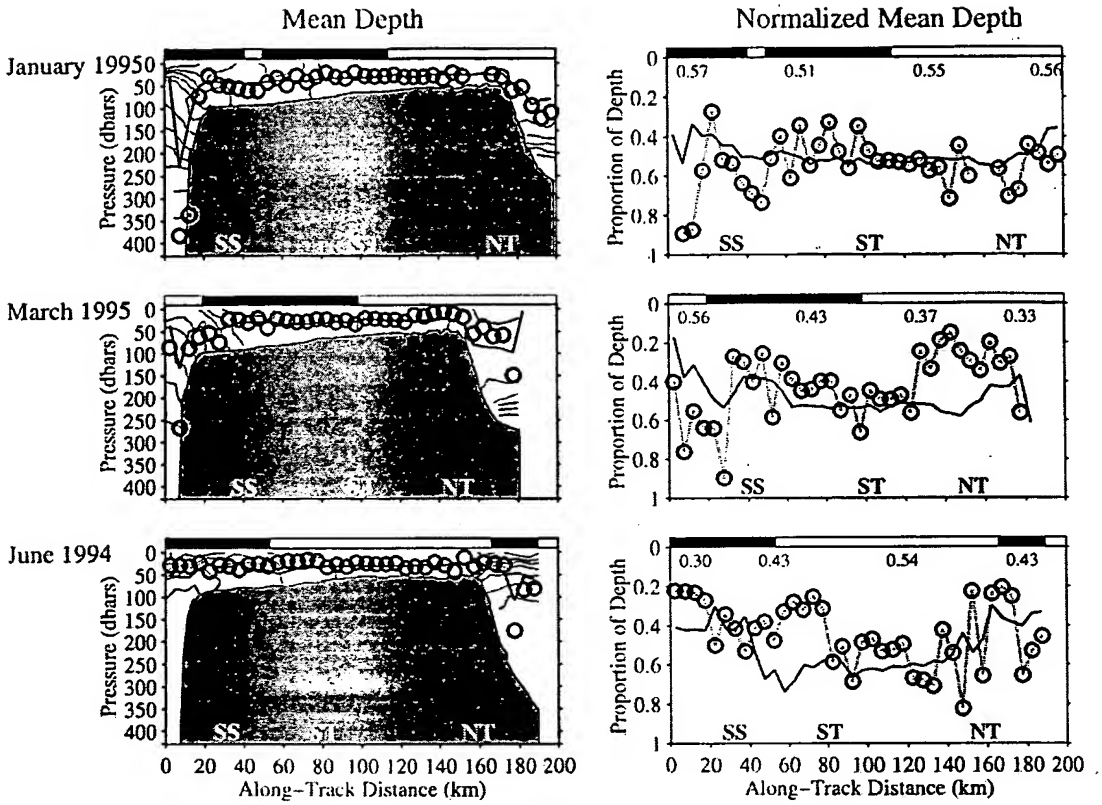

Fig. 7. Mean depth (left panels) and weighted mean depth (right panels) for the copepod *Calanus finmarchicus* (circles and dotted lines) and fluorescence (solid heavy line) across the three transects. Mean depth and weighted mean depth were calculated for all observations of these variables within 5 km along-transect distance intervals. The plot formats are as for Fig. 6, with periods of day and night, approximate cross-transect locations of frontal features, and distribution of isopycnals indicated with the thinner contour lines. The average weighted mean depth of *C. finmarchicus* was calculated within each of the cross-bank regions demarcated by fronts (seaward of Shelf-Slope Front, between Shelf-Slope and southern tidal mixing fronts, bank crest, and north of the northern tidal mixing front) and are indicated by the numbers on the right set of panels.

the Slope Water and Gulf of Maine during all three months; however, because of the low number of observations in these regions ($n = 6$–7), a significant difference between the two at the $p < 0.05$ level could not be achieved (Zar, 1984). Although *Calanus* is not considered strictly to be an herbivore (e.g., Landry, 1981; Barthel, 1988; Gifford, 1991; Kleppel, 1993; Ohman and Runge, 1994), phytoplankton (represented here by fluorescence) is one of the food sources for the animal. During January 1995, the mean depths of fluorescence and *Calanus* were positively correlated for all regions except the crest but showed weak positive or negative correlation for most regions during both March 1995 and June 1994 (Table 2), suggesting that the factors determining the depths of these two characteristics were different. Changes in the weighted mean depth of *Calanus* were not associated with the transitions between day and night, both for all data from each transect and for data within each region (Slope Water, southern flank, Crest, Gulf of Maine) for each month

Table 2
Correlation across the three transects and within each region between *Calanus finmarchicus* and fluorescence depth distribution, as expressed by the weighted mean depth (WMD) and normalized weighted mean depth statistics

Month	Region	*N*	Correlation coefficient	
			WMD	Normalized WMD
January 1995	Entire Transect	40	0.95[a]	− 0.01
	Slope Water	6	0.94[a]	0.26
	Southern Flank	14	0.86[a]	− 0.01
	Bank Crest	14	0.01	0.03
	Gulf of maine	6	0.88[a]	0.42
March 1995	Entire Transect	37	0.81[a]	− 0.09
	Slope Water	8	− 0.27	0.31
	Southern Flank	12	− 0.27	0.31
	Bank Crest	10	0.22	− 0.60
	Gulf of Maine	7	0.67	− 0.43
June 1994	Entire Transect	38	0.79[a]	0.36
	Slope Water	6	− 0.22	− 0.19
	Southern Flank	10	− 0.41	− 0.65[a]
	Bank Crest	15	− 0.22	− 0.19
	Gulf of Maine	7	− 0.33	− 0.91[a]

[a]Indicate coefficients which are significantly different from zero at $p < 0.05$ or better.

(Mann–Whitney *U*-Test, $p < 0.05$, Zar, 1984), supporting the observation that no diel vertical migration was occurring during these periods.

Greater variation was observed in the along-transect distribution of the normalized weighted mean depth for both *Calanus* and fluorescence (Fig. 7, right panels). Mean normalized weighted mean depths were calculated for each of the four geographic regions across the bank (south of the Shelf/Slope Front, southern flank, Crest, and north of the northern tidal mixing front) (Table 3). The normalized weighted mean depth may be utilized as an indicator of whether a vertical distribution is stratified, since values of the normalized WMD close to 0.5 may indicate a homogenous distribution. For January 1995, no significant differences in the normalized weighted mean depths of *Calanus* between the four regions were observed (Kruskal–Wallis test). A homogeneous distribution throughout the water column was observed in January 1995 in all regions except the bank crest where peak abundances were in the lower portion of the water column ($p < 0.03$); this apparent exception may be an artifact of the very low abundances observed in that region. For both March 1995 and June 1994, significant variations in the normalized weighted mean depth of *Calanus* between regions were observed (Kruskal–Wallis, $p < 0.03$ and $p < 0.083$ for March 1995 and June 1994, respectively). The NWMD of *Calanus* were shoaler on the Crest of the bank (0.37) and in the Gulf of Maine (0.33) than along the southern Flank (0.43) or Slope Water (0.56) during March 1995 (non-parametric post-hoc comparison of means, $p < 0.05$; Zar, 1984). Examination of the vertical distribution of *Calanus* (Fig. 6) revealed that in these two regions (southern Flank, Slope Water) *Calanus* was distributed homogeneously throughout the

Table 3
Average normalized weighted mean depths (NWMD) for *Calanus finmarchicus* and fluorescence for each of the four regions across each transect[a]

Month	Region	Average NWMD	
		C. finmarchicus	Fluorescence
January 1995	Slope Water	0.63A	0.42A,B
	Southern Flank	0.51 A	0.51B,C (0.03)
	Bank Crest	0.55 A (0.03)	0.53C (0.0002)
	Gulf of Maine	0.56 A	0.45A
March 1995	Slope Water	0.56A	0.39A (0.032)
	Southern Flank	0.43A, B	0.49A,B
	Bank Crest	0.37B,C (0.018)	0.54B (0.001)
	Gulf of Maine	0.33C (0.02)	0.47B
June 1994	Slope Water	0.30 A (0.006)	0.40A (0.0034)
	Southern Flank	0.43B,C (0.0014)	0.53B
	Bank Crest	0.54B	0.59B (0.00001)
	Gulf of Maine	0.43C	0.37A (0.001)

[a]For each month, the letters indicate regions for which the average normalized mean depths were not significantly different from each other ($p < 0.05$); the normalized mean depths for some regions were not significantly different from more than one other region and this is indicated with two letters. For example, the mean NWMD for January, 1995 was the same in all four regions (A). In March 1995, however, the mean NMWD for the southern flank was not different from that observed both in the Slope Water (A) and the crest (B). The numbers (in parenthesis) indicate the probability that the mean normalized depth is significantly different from 0.5 (*t*-test).

water column (also NWMD was not significantly different from 0.5). In contrast, in June 1994 *Calanus* were found shoaler in the Slope Water (0.3) than in the other three regions and deeper on the Crest of the bank (0.54) than in the Gulf of Maine (0.43) or on the southern Flank (0.43) (post-hoc comparison of means, $p < 0.05$). For both the Crest and Gulf of Maine, the normalized weighted mean depth was not significantly different from 0.5. Examination of the vertical distribution of *Calanus* (Figs. 6 and 7) confirmed this for the Crest while in the Gulf of Maine animals were found either in the upper water column near the northern tidal mixing front or at depth further to the north.

Regional differences were observed in the normalized weighted mean depths of fluorescence for all three months (Table 3). Fluorescence was relatively deeper in the water column over the southern flank and crest of the bank than in the Slope Water or in the Gulf of Maine. Stratification (normalized mean depth significantly different from 0.5) generally was observed in regions with elevated fluorescence across each of the transects.

3.3.2. *Hydroid colonies*

The asexual hydroid phase of cnidarians, when detached from their typical benthic habitat, potentially are important predators of young *Calanus* and larval fish on Georges Bank (e.g., Bigelow, 1926; Davis, 1987; Gallager et al., 1996; Madin et al., 1996). Hydroid colonies were conspicuous in the Video Plankton Recorder images, especially during March 1995 and June 1994

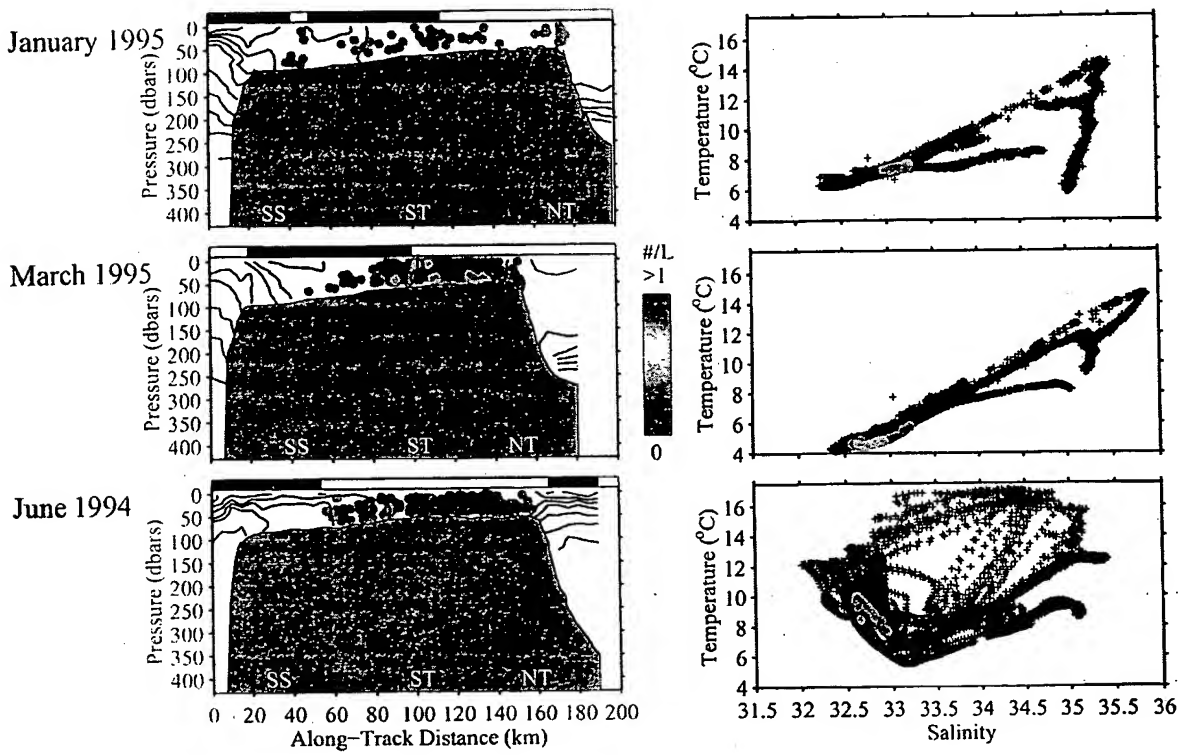

Fig. 8. Distribution of hydroid colonies across the three transects (left) and as a function of temperature and salinity (right). Plot format as for Fig. 6.

(Fig. 8). Lowest abundances of hydroid colonies were observed during January 1995, with progressively greater abundances during March 1995 and June 1994. Hydroids generally were confined to the crest of the bank in Georges Bank Water. Some colonies also were found in the Shelf Water to the south of the southern tidal mixing front during June 1994, but none were found in the Slope Water or in the Gulf of Maine. On the crest, hydroids were distributed homogeneously throughout the water column (note from Fig. 2 that the VPR did not survey to the surface during June 1994). Comparison of the distributions of *Calanus finmarchicus* and hydroid colonies from the three transects reveals that the distribution of hydroids during March 1995 corresponded to the region of greatest *Calanus* abundance while the distribution during June 1994 was associated with the region of lowest *Calanus* abundance.

3.3.3. Phaeocystis spp. protocolonies

One of the more intriguing taxa observed with the Video Plankton Recorder was the protocolonies of the colonial phytoplankton *Phaeocystis* spp. These smooth, ellipsoid objects were observed in great abundance during March 1995 and lower abundances during January 1995 (Fig. 9). Prior data on the distributional patterns of these delicate organisms was lacking owing to their very delicate nature and the lack of non-destructive sampling methods for quantifying their abundance. The distribution of *Phaeocystis* protocolonies was restricted mostly to the crest of the bank and

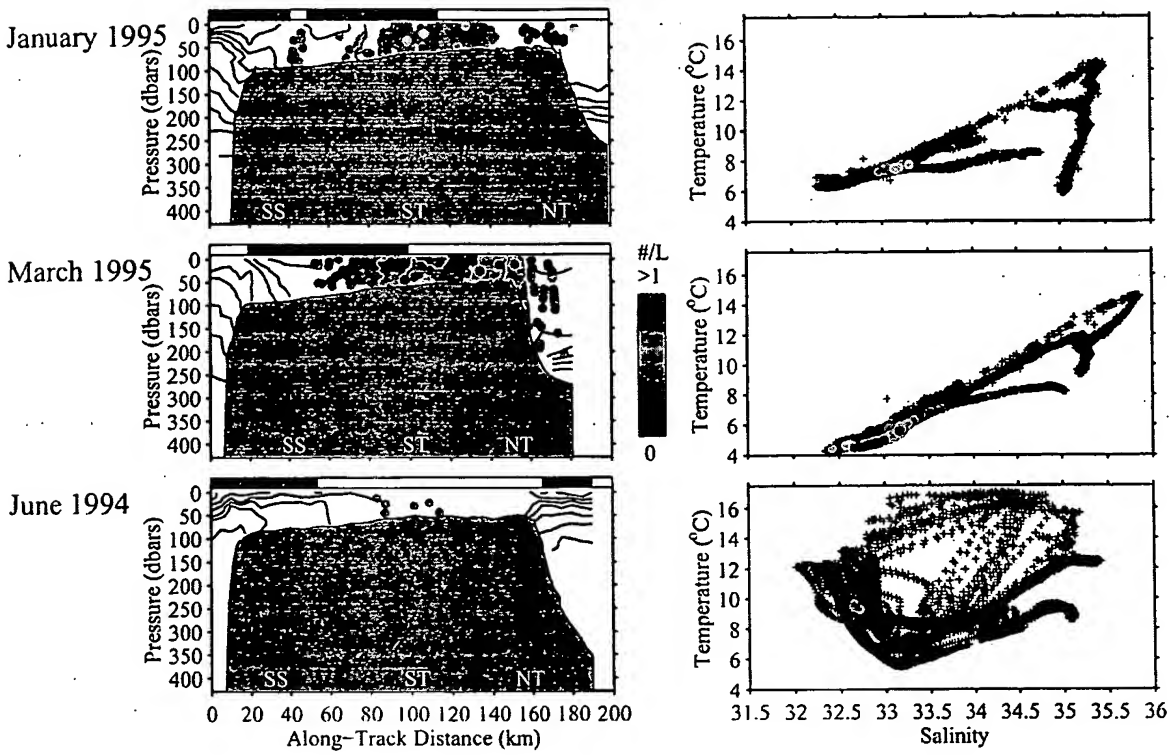

Fig. 9. Distribution of *Phaeocystis* spp. protocolonies across the three transects (left) and as a function of temperature and salinity (right). Plot format as for Fig. 6.

Georges Bank Water (between the tidal mixing fronts), although some colonies were observed both on the southern flank and in the Gulf of Maine. Very few protocolonies, or mature colonies, of *Phaeocystis* were seen in June 1994. The observed bloom of *Phaeocystis* may be an episodic event that does not occur annually.

3.3.4. *Pteropods*

Pteropods (likely *Limacina retroversa*; Redfield, 1939; Davis, 1987; Gallager et al., 1996) were present across Georges Bank during all three months; however, abundances and occurrence were dramatically reduced during June 1994 relative to both January 1995 and March 1995 (Fig. 10). Distribution was uniform and vertical homogeneous across the crest and southern flank of the bank during both January 1995 and March 1995, in the well-mixed Shelf Water and Georges Bank Water. Individuals were observed sporadically in the Gulf of Maine and Slope Water. During June 1994, few individuals were observed on the crest of bank and only a scant number were observed on the southern flank. The difference in seasonal abundance is likely due to life history characteristics of this cold-water species. Redfield (1939) described the counter-clockwise drift and population development of *L. retroversa* in the Gulf of Maine during spring and found a close association between population size structure and circulation.

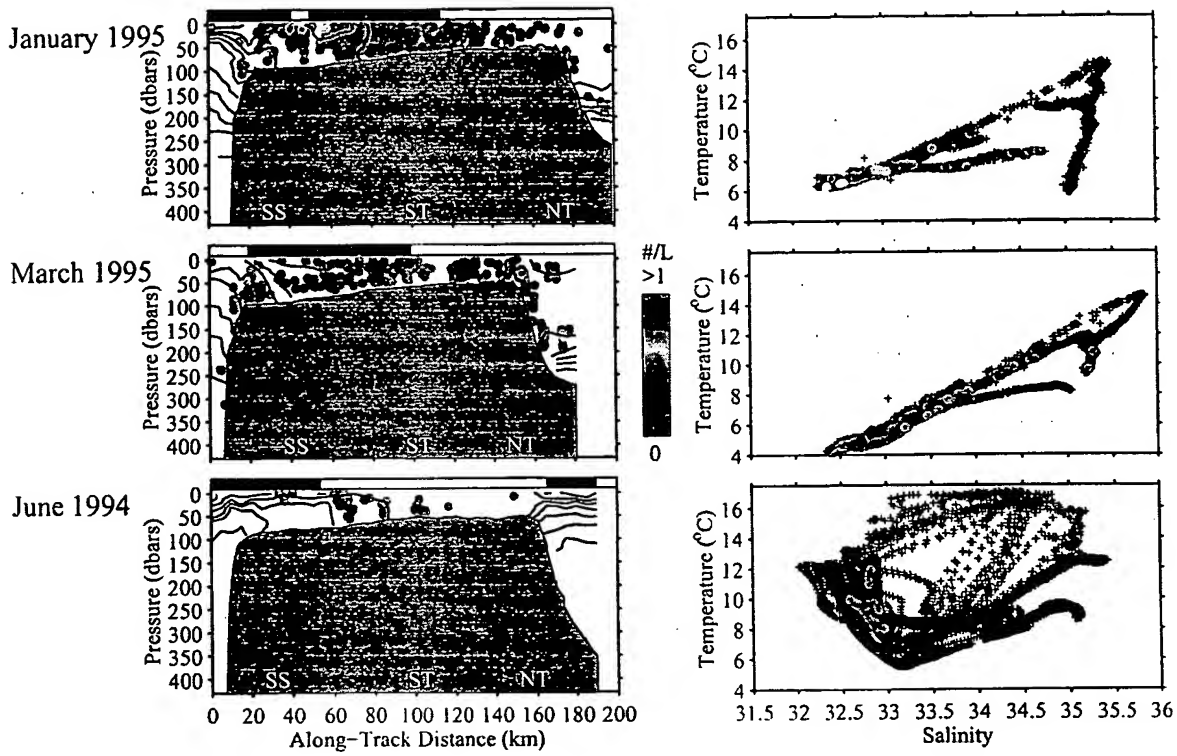

Fig. 10. Distribution of pteropods across the three transects (left) and as a function of temperature and salinity (right). Plot format as for Fig. 6.

3.3.5. *Marine Snow*

Marine snow was the most abundant category of plankton or particle identified (72.8, 61.2, and 80.3% of all images for January 1995, March 1995, and June 1994, respectively). Low concentrations were observed over most of the bank during January 1995 except in the Shelf Water between the Shelf–Slope and southern tidal mixing fronts (Fig. 11), where elevated concentrations were observed in at mid- and near-bottom depths. Concentrations across the bank were similar in March 1995, with nodes of elevated concentrations found on the southern flank and on the crest of the bank, in Shelf Water and Georges Bank Water. Greatest concentrations were found during June 1994 offshore of the southern tidal mixing front between the Shelf Water and Georges Bank Water. Few similarities between the distributions of marine snow and physical variables, fluorescence, light attenuation, and *Calanus* were observed (Table 1). Only on the bank crest in March 1995 was coincidence in the distribution of light attenuation and marine snow concentration observed. The mean diameter of marine snow varied significantly between months, with largest particles observed in March 1995 (2.1 ± 1.0 mm, $n = 29{,}641$), and smaller particles in January 1995 (1.9 ± 1.8 mm, $n = 10{,}497$) and June 1994 (1.8 ± 0.85 mm, $n = 23{,}679$) (mean $\pm$ SD; ANOVA, $p < 0.05$; Student–Newman–Keuls post-hoc test, $p < 0.05$; Zar, 1984). The larger size of marine

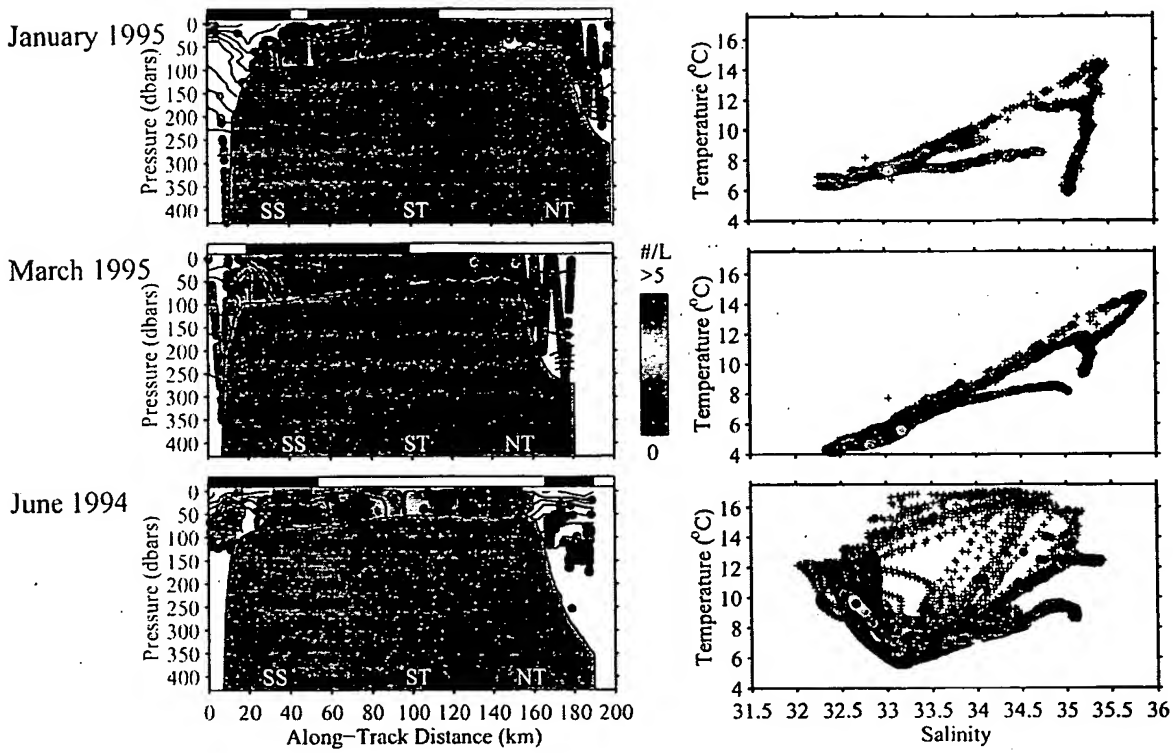

Fig. 11. Distribution of marine snow across the three transects (left) and as a function of temperature and salinity (right). Plot format as for Fig. 6.

snow particles in March 1995 may have resulted from the high abundance of material produced during primary production (e.g., decomposing phytoplankton, algal mats).

3.3.6. *Algal mats*

High abundances of algal mats, a type of marine snow composed of chains of diatoms were observed during March 1995 in the Shelf–Slope Front and Slope Water to the south of the bank (Fig. 12). The morphology of these large particles was similar to that described by Alldredge and Silver (1988) and likely resulted from elevated concentrations of chain diatoms produced during the spring bloom along the southern flank and in the Shelf–Slope front.

3.4. *Principal component analysis*

The first three modes of the principal component analyses explained up to 83% (for March 1995) of the total variability in the seven variables utilized and identified associations that were not robust in the correlation analysis; the fourth mode encompassed another ~13% of the total variability (Table 3). The normalized coefficients of each of the eigenvectors indicated the potential contribution of each variable to the principal component for that mode, with similar coefficients indicating similar weightings and opposing signs indicating a negative association. The spatial

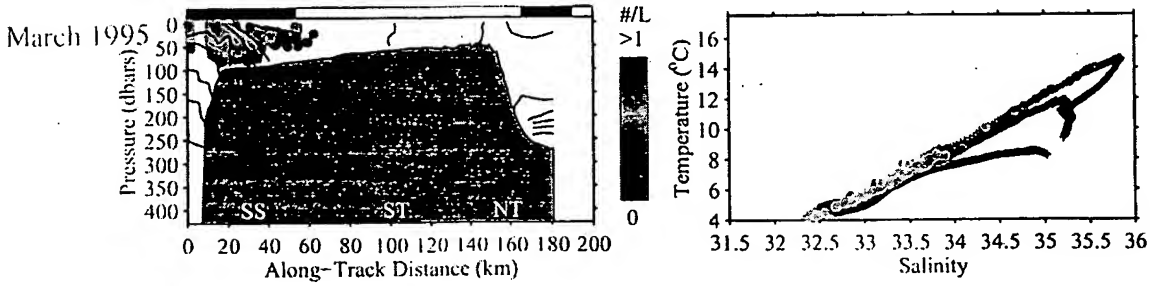

Fig. 12. Distribution of algal mats across the transect (left) and as a function of temperature and salinity (right) in March 1995. No algal mats were observed in January 1995 or June 1994. Plot format as for Fig. 6.

distribution of the principal components of each mode reflected the distributions of the variables with high coefficients for that mode. No association between *Calanus finmarchicus* and hydrographic (temperature, salinity, density) characteristics were observed, indicating that the distribution of *Calanus* was decoupled from that of the hydrography. For January 1995, hydrography, fluorescence, and light attenuation were strongly associated in the first mode; a negative association between marine snow concentration (1.00) and fluorescence (− 0.788) and attenuation (− 0.837) was seen in the second mode. Together the first two modes explained over ~ 62% of the total variance. The spatial distributions of the first modes (Fig. 13) was similar in many respects to the mesoscale distribution of water mass types across the bank, while that of the second mode was strongly influenced by elevated concentrations of marine snow on the southern flank and in the upper Gulf of Maine, which were associated with (a) near-constant hydrographic characteristics and (b) decreasing values of fluorescence and light attenuation. This suggests that the marine snow was composed of detrital rather than fluorescing material. The third mode was almost exclusively influenced by *Calanus finmarchicus*, explaining ~ 14% of the variance. The spatial distribution of this mode (not shown) resembled the distribution of *Calanus* across the bank. The fourth mode embodied variation primarily in the concentration of marine snow. For March 1995, hydrographic (temperature, salinity, density) characteristics again were strongly associated and their variability was expressed by Mode 1 (~ 46% of the total variance). Fluorescence and light attenuation were not as strongly associated with hydrography as observed in January 1995 and were the dominant variables in Mode 2 (23% of the total variance). *Calanus* was the dominant variable in Mode 3. No association was seen between fluorescence and light attenuation and *Calanus* or marine snow. The fourth mode was dominated by marine snow (~ 13%). Again, the spatial distribution of the first principal component strongly resembled that of the hydrographic features. The potential presence of a Scotian Shelf Water intrusion is seen in the across-transect distribution of the first principal component as the low value located at 20–40 km along-track distance and between 0 and 50 m (Fig. 13). The distribution of the second principal component was similar to those of fluorescence and light attenuation. Associations between variables differed in June 1994. Temperature was not associated with salinity and density, indicating that salinity may have been the primary determinant of density at this time (but see cross-transect distributions of temperature and density) and perhaps reflecting the modification of temperature from insolation and the onset of stratification. Light attenuation, and to a lesser extent fluorescence, was associated negatively with salinity and

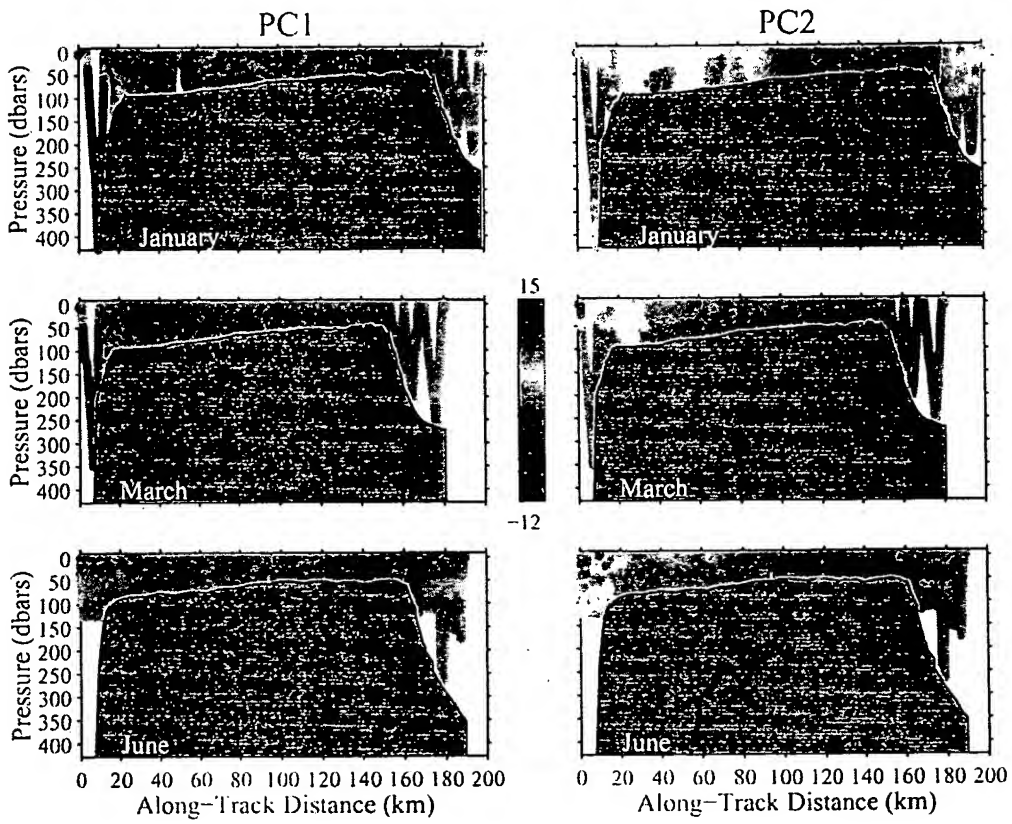

Fig. 13. First and second principal components plotted as a function of distance and pressure for the three transects. The distance–depth location of each data point is plotted as a dot, with the color of the symbol representing the magnitude each principal component for that location. The values of principal component 2 for June 1994 were multiplied by 10 prior to plotting in order to better show variations in magnitude.

density in the first mode which explained ~ 48% of the total variance. The spatial distribution of the first principal component was similar to those of salinity, density, light attenuation, and, to some degree, fluorescence. This mode, then, described the association between water mass types and the relative concentrations of particulates measured by light attenuation and fluorescence. The second mode was influenced strongly by temperature with some association seen between fluorescence (negative) and *Calanus* (positive); this mode explained ~ 16% of the total variance. The distribution of this mode resembled that of temperature. The third mode (15.7%) was influenced by marine snow, with some negative association seen between marine snow and fluorescence and temperature. Not until the fourth mode (14.9% of the total variance) is the abundance of *Calanus* important, with only some negative association between *Calanus* and temperature present. Note that little association between *Calanus* and hydrographic characteristics, biological variables, or marine snow also was seen in correlation coefficients (Table 1). The association between fluorescence and light attenuation was not as strong during June 1994 as for the other two months, which was not surprising considering the distribution of these variables (Fig. 5). Principal component

analysis, then, was used to identify statistically mesoscale distributions, associations, and patterns observed visually in the data and identified the proportion of the total variance in the data set that was accounted for by each type of distribution.

3.5. *Flux of Calanus*

Velocities averaged over selected depth ranges of the upper water column demonstrated the classic Georges Bank circulation, with strong easterly advection concentrated in a jet along the northern edge and more diffuse westerly circulation across the southern flank of the bank (Fig. 14). Velocities in the Gulf of Maine (north of the 200 m isobath) were oriented in a northeasterly direction. Slope Water velocities (between 200 and 2000 m isobaths) were generally southeasterly, although surface depths demonstrated a more southerly direction. Northerly velocities in the on bank direction were observed at depth (176–208 m) in the Slope Water.

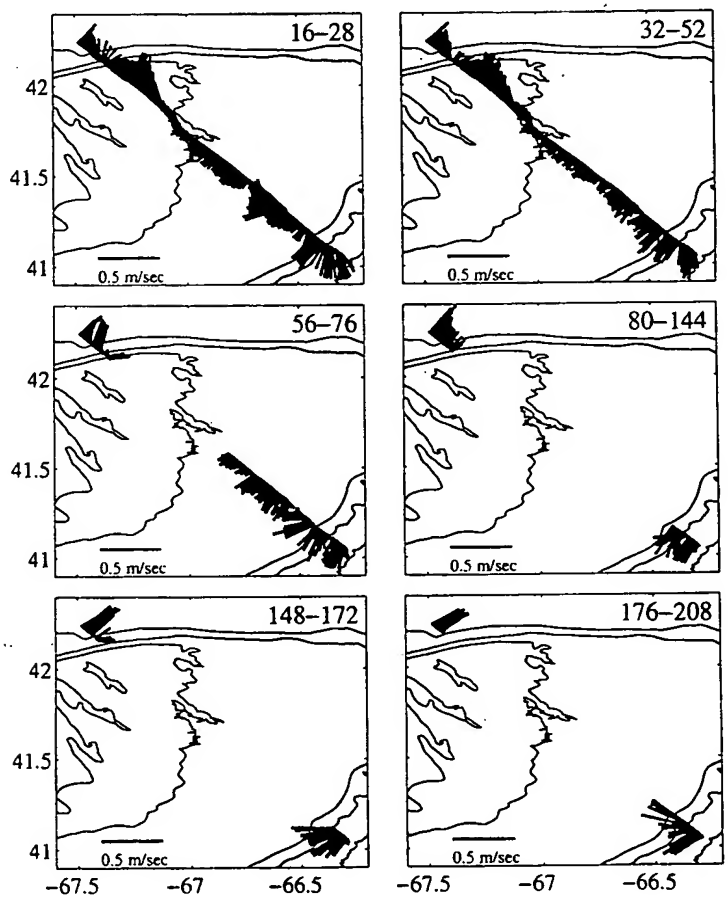

Fig. 14. Acoustic Doppler current profiler velocities, averaged over selected depth intervals, across the transect for January, 1995. Depths over which velocities were averaged were selected by examination of the velocities at all depths to identify depths for which the magnitude and direction of velocities were similar. Bottom contours of 40, 60, 100, 200, and 100 m are shown.

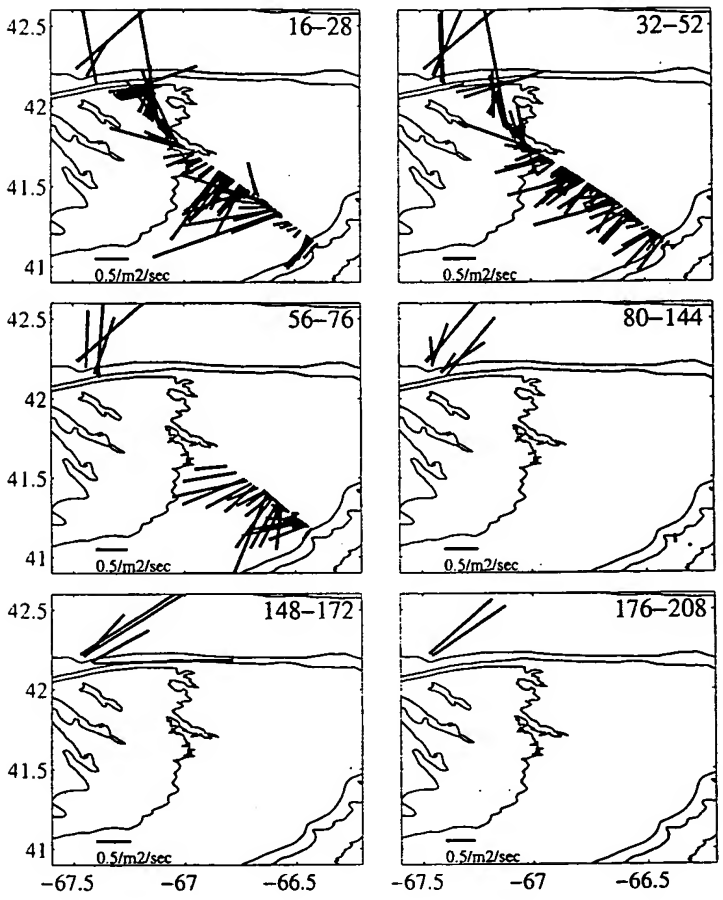

Fig. 15. Flux of the copepod *Calanus finmarchicus* across the transect in January, 1995. Flux estimates were derived by multiplying the depth-averaged velocity vectors (Fig. 15) by the abundance of *C. finmarchicus* in that depth-cross-stream location data bin. No flux estimates were derived for locations where no *C. finmarchicus* were observed. Bottom contours of 40, 60, 100, 200, and 100 m are shown.

The flux of *Calanus* on the bank itself followed the anticyclonic circulation around the bank, with little evidence of either off- or on-bank transport (Fig. 15). The jet along the northern edge of the bank appeared to concentrate *Calanus* into the center of the current in the upper water column (16–52 m). Flux of *Calanus* in the Gulf of Maine (north of 100 m isobath) was oriented away from the bank for all depths, indicating that little input *Calanus* onto the bank from the Gulf of Maine was occurring.

3.6. Spectral analysis

Much of the larger-scale variability in the spectra can be attributed to the vertical structure of the water column (Fig. 16). Because the data were collected along a towyo path, temporal changes in the spectra are relatively equivalent to spatial changes. For pressure and the hydrographic

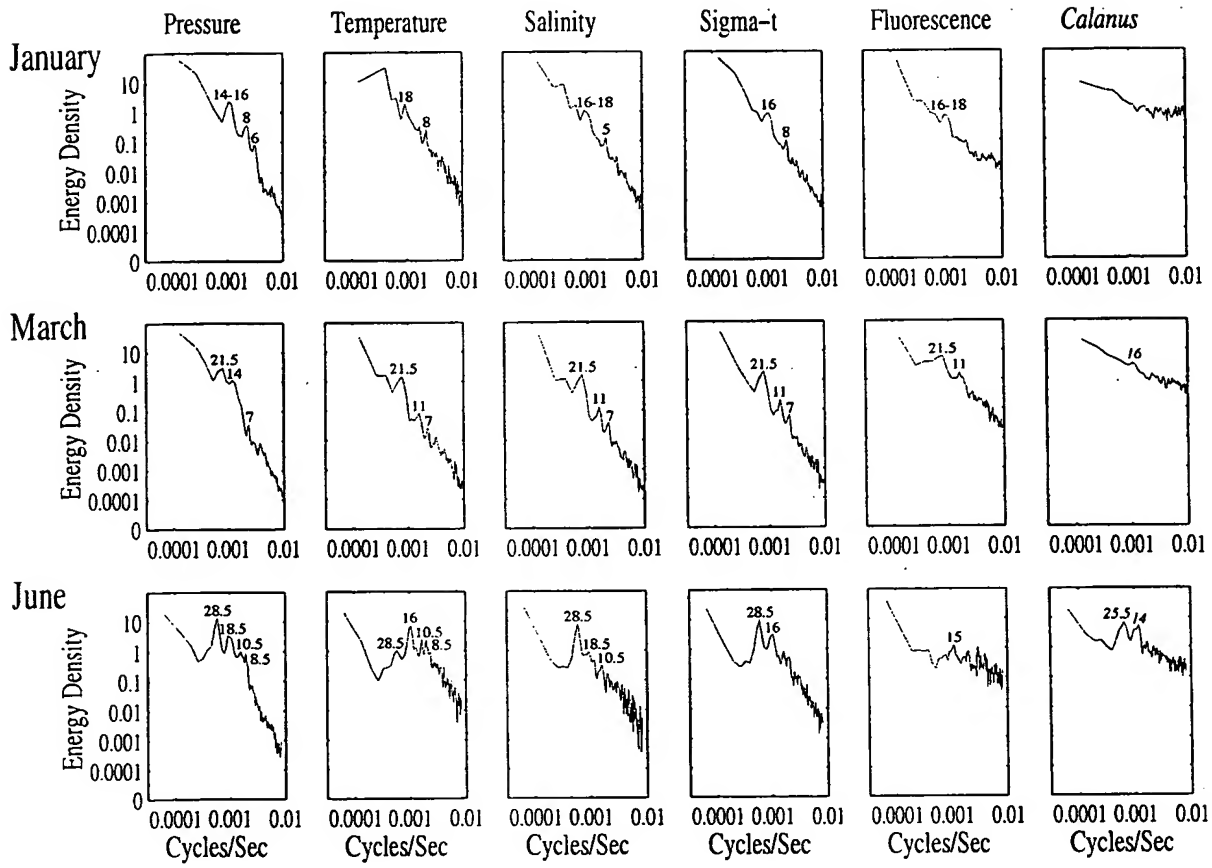

Fig. 16. Spectral analyses for pressure, temperature, salinity, sigma-*t*, fluorescence, and *Calanus finmarchicus* abundances for the three transects. Period in minutes of dominant peaks are noted on each panel; those not associated with the towyo period and vertical structure of the water column are indicated in italics.

variables, several pronounced peaks in each spectra were associated with the time interval of the towyo; the periods of the towyos varied with water depth, and hence location across the transect, and from cruise to cruise. The spectra of the reference variable, pressure, demonstrate the period of the towyos for each cruise. Vertical structure in hydrographic features was much more pronounced during June 1994 than the winter/spring months (Fig. 3). Consequently, towyo effect peaks resulting from the vertical structure of the water column and period of the towyos at the different across bank locations were observed at multiple periods for both the reference and hydrographic variables during that month.

Overall, greater energy was present in the spectra of the biological variables (fluorescence and *Calanus*), especially at longer time periods. Small-scale variability (higher energy) was greater for plankton (fluorescence and *Calanus*) than for hydrographic variables (temperature, salinity, density). The effect of vertical structure was much reduced in the spectra of the biological variables (fluorescence and *Calanus*) (Fig. 16) and was more prominent in the spectra of fluorescence than

Table 4
Eigenvectors of the first four modes from the principal component analyses for the three transects[a]

	Mode 1	Mode 2	Mode 3	Mode 4
January, 1995				
Temperature	0.799	−0.413	−0.114	0.217
Salinity	1.000	−0.528	0.025	0.287
Sigma-*t*	0.902	−0.489	0.091	0.273
Fluorescence	−0.830	−0.788	0.037	0.400
Attenuation	−0.801	−0.837	0.078	0.422
C. finmarchicus	0.068	0.303	1.000	0.143
Marine snow	−0.046	1.000	−0.198	1.000
% Total variance	45.2	17.5	14.3	12.600
Cumulative %	45.2	62.7	77.0	89.600
March, 1995				
Temperature	0.966	0.345	−0.022	0.078
Salinity	1.000	0.325	−0.008	0.137
Sigma-*t*	0.963	0.316	−0.013	0.181
Fluorescence	−0.576	0.939	0.005	0.066
Attenuation	−0.491	1.000	0.024	0.083
C. finmarchicus	−0.081	−0.119	1.000	0.439
Marine snow	−0.272	−0.221	−0.437	1.000
% Total variance	45.7	23.0	14.3	13.3
Cumulative %	45.7	68.7	83.0	96.3
June, 1994				
Temperature	−0.187	1.000	−0.532	−0.445
Salinity	0.972	0.121	−0.289	−0.260
Sigma-*t*	1.000	−0.386	−0.006	−0.033
Fluorescence	−0.683	−0.548	−0.516	−0.159
Attenuation	−0.973	−0.183	−0.092	−0.056
C. finmarchicus	−0.024	0.448	−0.156	1.000
Marine snow	−0.257	0.335	1.000	−0.243
% Total variance	40.2	16.2	15.7	14.9
Cumulative %	40.2	56.4	72.1	87.0

[a]The percentage of the total variance explained by each mode also indicated. For June 1994 only those data where the temperature was less than or equal to 13°C were employed in the analysis.

those of *Calanus*. For all three months, the towyo effect peaks associated with data collected on the southern flank were present in the fluorescence spectra, although the shorter period peak (constant variable effect) was present only in the June 1994 spectrum. For *Calanus*, no apparent effect of vertical structure was observed during January 1995, when the vertical distribution was fairly homogeneous (Figs. 6 and 7). The energy peaks in March 1995 (16 mins) and June 1994 (14, 25.5 minutes) were not associated clearly with vertical structure or the towyo period. For both March 1995 and June 1994, these energy peaks for *Calanus* were located on the spectra at times sufficiently similar to those of the pressure towyo effect peaks from locations where the animal was

most abundant (the crest for March 1995 with a towyo effect peak of 11–14 min and the southern flank/northern edge for June 1994 with a towyo effect peak of 16 min) that the *Calanus* spectral peaks may have resulted from variability in the abundance maximum at adjacent towyos or from patchiness in the upper water column.

4. Discussion

High-resolution descriptions of water mass, plankton, and particle distributions across Georges Bank were obtained in the present study. The coincidence of biological and physical measurements permitted a closer and higher resolution examination of the association between these variables than is usually possible using conventional biological sampling methods. Only a few previous studies of the plankton distributions across on Georges Bank have achieved such high vertical (1 m) and horizontal (1 km) resolution (e.g., Benfield et al., 1996; Gallager et al., 1996; Norrbin et al., 1996), since most taxon specific biological sampling has been conducted at horizontal separations of kilometers and with vertical resolution of multiple meters (e.g., Durbin et al., 1997) or total water column (e.g., Davis, 1987; Meise and O'Reilly, 1996). Such high-resolution data now permits biologists to examine variability with tools such as principal component analysis and spectral analysis which previously have been utilized primarily in the analysis of physical data (e.g., Preisendorfer, 1988) or to identify associations between different taxa from net or bottle sampling (e.g., Denman and Platt, 1978).

The distributions of plankton and particles clearly were associated with the different water masses. For most taxa, these distributions, did not vary during the different months sampled, although abundances changed markedly (e.g., *Phaeocystis* protocolonies, hydroids, pteropods). For *Calanus finmarchicus*, seasonal changes in its association with a particular water mass type also was demonstrated. Although taxon–water mass associations were observed on a regional or mesoscale, biological and physical characteristics were decoupled on smaller scales so that little correlation between physical properties (e.g., temperature) and plankton abundance (e.g., *Calanus*) was observed.

The structure of the physical environment (density, temperature/salinity, advection) on Georges Bank during the three transects was representative of typical conditions and exhibited frontal features and regional water mass characteristics described previously (e.g., Hopkins and Garfield, 1981; Flagg, 1987; Butman et al., 1987). Deviations from the mean characteristics were observed in association with advective or dynamic events. For example, the Shelf–Slope Front was distinct across all three transects; however, the width of the feature and the inclination of the isopycnals varied according to the influence of dynamic features (e.g., rings or eddies) offshore of the bank. Such mesoscale features also produced the high temperatures and salinities observed during the June 1994 transect, as water of Gulf Stream origin mixed with upper Slope Water along the southern edge of the bank. The presence of Scotian Shelf Water on the southern flank in March 1995 occurred during episodic advective injection of Scotian Shelf Water across the Northeast Channel onto the bank (e.g., Bisagni et al., 1996; Smith et al., 2001).

Principal component analysis and correlations between physical and biological variables revealed differences between the winter–early spring (January 1995, March 1995) and early summer (June 1994). For example, salinity appeared to be important in determining density during June

1994 while both salinity and temperature were important in January 1995 and March 1995. Close association between fluorescence and light attenuation during January 1995 and March 1995 indicated that most particles measured by light attenuation may have contained viable chlorophyll, indicative of recent primary production. By contrast, little association was seen between fluorescence and light attenuation in June 1994, suggesting that the particles during that period may have been detrital. Furthermore, no association was seen between light attenuation and marine snow. Note also that only in June 1994 was a negative association (PCA; Table 4) between *Calanus* and fluorescence observed, suggesting either that differing mechanisms are determining the abundance of the two or, potentially, that grazing by *Calanus* on fluorescing particles had occurred. Principal component analysis also demonstrated that much of the overall variability in the data sets was derived from the across-bank presence of different water mass types and regimes, since the spatial distribution of the first mode (representing half of the total variability) resembled strongly the across bank distribution of water masses. These observations suggest that very different physical and biological regimes existed in early winter/late spring vs. early summer.

Despite the obvious coincidence of particular taxa and water mass characteristics, as observed both in the cross-transect distributions and temperature–salinity–plankton plots (Figs. 6–12), no statistical relationships (e.g., correlation, principal component analysis) could be identified between the distributions of *Calanus* and marine snow and fluorescence, light attenuation, or hydrographic characteristics. This may be a consequence in part because of the disparate nature of plankton abundance (discrete) vs. hydrographic (continuous) data. Additionally, a particular hydrographic condition (e.g., temperature range) may exist simultaneously in multiple water masses but a particular taxon is confined to a single water mass; hence, correlation coefficients would not show a relationship between that temperature range and the taxon's abundance since variation in the magnitude of the two variables would not co-vary over all the observations. This likely accounts for the lack of correlation (correlation coefficient) between *Calanus* and fluorescence during June even though principal component analysis indicated that there was association between the two. Hence, the distribution of taxa observed on Georges Bank resulted either from advection of plankton onto the bank in particular water masses or, more likely, from establishment of populations on the bank in specific regions, rather than resulting from a behavioral response by the taxon to locate preferred temperature or salinity characteristics.

Spectral analysis of the biological and hydrographic data revealed that, although some variability in the distribution of plankton and physical variables occurred on similar spatial/temporal scales, variability in the distribution of plankton at the small scale was greater than that observed either for hydrographic variables or for the reference variable of pressure. These results suggest that water mass characteristics probably were not the dominant influence on the distribution of plankton at small scales and that biologically induced patchiness may have accounted for the small-scale variability, as has been demonstrated in previous VPR studies (e.g., Davis et al., 1992b; Gallager et al., 1996).

Calanus finmarchicus was the dominant zooplankton taxon present in the size range imaged by this configuration of the Video Plankton Recorder. Distributions of *Calanus* were consistent with those observed in previous and ongoing investigations of the Georges Bank ecosystem (e.g., Davis, 1987; Meise and O'Reilly, 1996; Durbin et al., 1997). The distribution and associations of *Calanus* with particular water masses and regions on the bank are believed to result from the interaction of

life history characteristics (e.g., vertical distribution, timing of reproduction) and advection which transports populations of the copepod onto Georges Bank (e.g., Davis, 1987; Meise and O'Reilly, 1996; Durbin et al., 1997; Lynch et al., 1998). Despite the inability of the VPR to distinguish between the different life stages of *Calanus finmarchicus*, the results of the present study still can be interpreted in the context of our understanding of these processes and interactions. During winter and spring, C. *finmarchicus* was found across the bank in both the Georges Bank and Shelf Water masses, as well as in the Gulf of Maine and in Lower Slope Water. By summer, however, populations of C. *finmarchicus* in Georges Bank Water (well mixed, crest of the bank) had diminished considerably while populations in the Shelf Water to the south and the northern tidal front (Surface and Intermediate Maine Water) were enhanced.

Off bank populations are thought to be the sources for repopulation of *Calanus* on Georges Bank during winter and early spring. *Calanus* spends the summer and fall at depth in the Basins of the Gulf of Maine or Scotian Shelf, migrating to surface waters in early winter to initiate reproduction (e.g., Davis, 1987; Durbin et al., 1997). Following ontogenetic migration of *Calanus* to the upper water column in the Gulf of Maine, populations on the bank should be renewed annually by several mechanisms including episodic advection of Gulf of Maine Water onto the bank along the northern edge during storms, non-storm-related advection of Gulf of Maine water onto the bank, or input from the Great South Channel region in the northeasterly flowing gyral circulation at the northern edge of the bank (e.g., Perry et al., 1993; Lewis et al., 1994; Limeburner and Beardsley, 1996; Durbin et al., 1997; Hannah et al., 1998; Lynch et al., 1998). Significant input of *Calanus* occurs in the Northeast Peak Region (e.g., Durbin et al., 1997; Lynch et al., 1998). The distributions of *Calanus* observed in the present study during January 1995 and March 1995 are consistent with these hypothesized repopulation mechanisms. Low abundances of *Calanus* were present on the bank during winter (January 1995) with greater abundances observed in the Lower Slope Water to the south and in the Maine Bottom Water to the north of the bank. Flux of *Calanus* (Fig. 15) indicated that transport of *Calanus* in upper portion of the water column from the west in the gyral circulation was occurring, with little input from the Gulf of Maine at this time. The apparent inconsistency between the flux of *Calanus* observed in this study and the mean circulation and mean flux of *Calanus* described in modeling efforts (e.g., Hannah et al., 1998; Lynch et al., 1998) may simply have resulted from variability in the circulation with low levels of Ekman flow occurring during this period. The relative importance of such wind-driven transport relative to that occurring in the easterly jet of the anticyclonic gyre cannot be assessed in the present study. By March 1995, *Calanus* was observed across Georges Bank and in the Gulf of Maine, with greatest abundances in the Georges Bank Water on the crest of the bank and in the surface waters of the Gulf of Maine and little or no *Calanus* in the Upper Slope Water to the south of the bank. The presence of *Calanus* on the crest of the bank implies that advection of Gulf of Maine and northern flank water across the northern tidal mixing front and easterly jet must have occurred in order to establish a seed population for subsequent reproduction, although this input was not obvious in the velocity or flux vectors observed during January 1995 (Figs. 14 and 15). During June 1994, greatest abundances of Calanus were found in the upper portion of the water column both on the southern flank and along the northern edge of the bank; the anticyclonic gyral circulation is strongest in these regions and at these depths and hence these populations of *Calanus* likely were transported to the NE (northern edge) or to the SW and potentially off the bank (southern flank) (e.g., Limeburner and Beardsley, 1996).

Input of *Calanus* to Georges Bank also may occur during episodic influx of Scotian Shelf Water to the bank (e.g., Bisagni et al., 1996; Durbin et al., 1997; Lynch et al., 1998). However, abundances of *Calanus* in the Scotian Shelf Water observed across the March 1995 transect were reduced relative to abundances at depth and inshore of the feature, indicating that this particular event did not input significant quantities of *Calanus* to the bank at this time.

Similarities in the temperature–salinity characteristics of Lower Slope Water and Maine Bottom Water, and the presence of a physical input mechanism of Lower Slope Water to the deep Gulf of Maine via the Northeast Channel (e.g., Ramp, 1986; Smith et al., 2001) suggest that the populations of *Calanus* observed during the present study in these water masses may have originated from a common, up-stream source along the Scotian Shelf. The acoustic Doppler current profiler velocity vectors from January 1995 demonstrated that little input of Lower Slope Water onto Georges Bank occurred along the southern flank during the sampling period. Temperature–salinity characteristics of the water surveyed on the southern flank also showed that no Lower Slope Water was found on Georges Bank. Therefore it is possible that the mechanism for input of Slope Water populations of *Calanus* to Georges Bank was influx of Lower Slope Water into the deep Gulf of Maine, rather than direct advection from the Slope Water along the southern flank of the bank.

Alternatively, the association of the *Calanus* with Maine Bottom Water and Lower Slope Water could have been due simply to downward seasonal vertical migration by animals produced in the upper waters of the shelf. The seasonal cycle of the vertical distribution of *Calanus* in the Slope Water (Miller et al., 1991) shows that the population is present in the surface waters of the slope during May and resides at a depth of $\sim$ 300–500 m during the rest of the year. It is well known that spring *Calanus* populations in the open ocean are produced in surface waters and then migrate to great depth ($\sim$ 500 m) for the rest of the year to over summer or overwinter (depending on latitude) (e.g. Fulton, 1973; Williams, 1985; Miller et al., 1991). In shelf regions, animals transported off the shelf by advection would migrate to their desired depth of $\sim$ 500 m, but animals remaining over the shelf may become trapped in basins such as in the Gulf of Maine (Bigelow, 1926; Davis, 1987; Lynch et al., 1998) and Santa Barbara Basin (Osgood and Checkley, 1997). This scenario readily explains the association of *Calanus* with the T–S properties seen in the VPR data, i.e. the *Calanus* in the deeper waters of the Gulf of Maine and Slope Water in January 1995 resulted from seasonal downward migration the previous year. Further data and biological/physical modeling of the Northeast Channel and Shelf/Slope region is needed to determine whether the deep Slope Water population is a significant source of *Calanus* to the Gulf of Maine or whether it is just a spill-over from the productive shelf region.

Distributions of *Calanus* during June 1994 were typical of summer and fall (e.g., Davis, 1987; Meise and O'Reilly, 1996; Durbin et al., unpublished data). Greatest abundances were seen in stratified waters over the southern flank and in the Gulf of Maine, with a prominent "hole" in the distribution over the crest of the bank, which has been previously described (Davis, 1987; Miese and O'Reilly, 1996). The elevated abundances resulted both from advection and in situ reproduction. Mature individuals on the southern flank would have to be introduced onto Georges Bank at the Northeast Peak as younger stages approximately 30 days earlier, according to mean circulation velocities (e.g., Limeburner and Beardsley, 1996; unpublished data) or considerably earlier if the individuals originated on the bank from the Great South Channel. For animals introduced via the latter mechanism, sufficient time would have elapsed between the introduction of actively

reproducing adults at the Great South Channel in winter (January 1995) and June 1994 for animals produced by the new populations to have matured to copepodites or adults (e.g., Durbin et al., unpublished data; Campbell et al., in press). The elevated abundances of *Calanus* coincided with high fluorescence in the Shelf–Slope Front. These stratified regions, therefore, are favorable locations for large secondary producers such as *Calanus*.

The low abundance of *Calanus* in Georges Bank water at the crest of the bank in June 1994 may have resulted from a combination of high predation pressure and semi-isolation, and hence reduced immigration of plankton, of that region by the strong anti-cyclonic circulation and well-established tidal mixing fronts. High abundances of hydroid colonies, a potential predator of early and mid-life stage copepodites of *Calanus*, were observed in the Georges Bank water during June 1994 (Madin et al., 1996; Bollens et al., 2001). The distribution and temporal patterns in abundance of planktonic hydroids seen in the present data are consistent with those reported from other investigations (e.g., Bigelow, 1926; Gallager et al., 1996; Madin et al., 1996; Concelman et al., 2001). Planktonic occurrence of these primarily benthic forms occurs through mechanical dislodgment of the organisms from the bottom by storms, tidal mixing, or bottom fishing (Bigelow, 1926; Madin et al., 1996; Concelman et al., 2001). Historically, highest abundances of planktonic hydroids have been observed on the Crest of Georges Bank in late spring and early summer (Bigelow, 1926; Concelman et al., 2001), probably because the circulation retains water on the Crest at this time (e.g., Limeburner and Beardsley, 1996). In addition to hydroids, other zooplankton taxa including chaetognaths, amphipods, and euphausiids also may exert considerable predation pressure on copepod populations on Georges Bank, in particular over the crest of the bank where high abundances of these predators have been observed (e.g., Whiteley, 1948; Davis, 1987; Avery et al., 1996; Sullivan and Meise, 1996). Hence, predation likely reduces populations of *Calanus* on the crest of the bank. This predation, in combination with the semi-isolation of the crest resulting from the establishment of the strong, anticyclonic circulation gyre, contributed to the low abundances of *Calanus* observed over the crest in June 1994.

The vertical distribution of *Calanus* in the different regions across the transect varied with season. In general, the animal was distributed homogeneously throughout the water column during periods when the physical and food environment was homogeneous. During January 1995, *Calanus* was distributed homogeneously throughout the water column in all regions except the Slope Water, coincident with the lack of significant vertical structure in the environment and with the uniform distribution of phytoplankton food (fluorescence). In March 1995, however, *Calanus* were found in the upper third of the water column in both the crest and in the Gulf of Maine, despite a lack of vertical structure in the environment of these regions. This vertical distribution of *Calanus* may have resulted from the ontogenetic migration from depth to the surface during the winter/early spring in the Gulf of Maine with the similarity in distribution potentially indicating that populations on the crest originated in the Gulf of Maine. During June 1994, *Calanus* was distributed homogeneously throughout the water column only on the well-mixed, and environmentally homogenous, crest of the bank. Similar results were observed for stage-specific vertical distributions from net and pump plankton samples (Durbin, pers. comm.).

No diel variation in the vertical distribution of *Calanus* was observed, in any of the regions. Diel vertical migration on the crest and southern flank of the bank generally has not been observed for *Calanus*, although it is typical for the species under certain environmental and food conditions in the deeper regions of the Gulf of Maine and Great South Channel (e.g., Durbin et al., 1995; Wishner

et al., 1988, 1995; Durbin et al., 1997). The number of day-night transitions and limited temporal coverage during the present study were insufficient to identify whether diel vertical migration was occurring in the deeper Slope Water and Gulf of Maine.

Little or no vertical structure was seen in the distribution of the other relatively abundant taxa (pteropods, *Phaeocystis* protocolonies, hydroids) during any of the three months examined. Of the three, only pteropods should be capable of sufficient vertical swimming to influence vertical distribution. The pteropod *Limacina retroversa* has been observed in association with specific environmental conditions and vertical structure of the water column (e.g., Gallager et al., 1996). In the present study, pteropods were abundant primarily during periods and in regions of low stratification (e.g., January 1995; March 1995; crest of the Bank), which may account for their lack of depth preference. Both hydroids and *Phaeocystis* protocolonies are non-motile and only marginally more dense than seawater, hence their vertical distribution should be dependent on physical mechanisms such as turbulence, mixing, and stratification, which produced a well- mixed water column, and homogeneous vertical distribution, during periods when these taxa were abundant.

Previous studies on the distributions of pteropods (*L. retroversa*) in the Gulf of Maine and on Georges Bank together demonstrated that high interannual variability is typical (e.g., Bigelow, 1926; Redfield, 1939; Riley and Bumpus, 1946). It has been hypothesized that populations of pteropods (*L. retroversa*) in the Gulf of Maine are augmented during winter (December) and spring (April) by influx from the Scotian Shelf (e.g., Redfield, 1939). The cyclonic basin-wide circulation then would advect populations on the bank at some later date. However, both the present study and that of Clarke and Bumpus (1946; as cited in Davis, 1987) demonstrated elevated abundances of pteropods during January with decreasing abundances throughout the spring and early summer, suggesting either that injection of pteropod populations occurs directly from the Scotian Shelf onto the bank in winter (January) or that population abundance on the bank is governed by additional yet unidentified mechanisms. Influx of Scotian Shelf Water onto Georges Bank itself during late winter and spring has been shown highly variable between years (Bisagni et al., 1996), which also may account for the differences in pteropod abundance patterns observed between studies. Despite a demonstrated strong affinity for Slope Water (e.g., Chen and Hillman, 1970), pteropods were not particularly abundant in Slope Water to the south of the bank or in deep Gulf of Maine Water.

A strong fluorescence signal was associated with the Shelf–Slope Front during both March 1995 and June 1994 (Fig. 5). Elevated fluorescence associated with the Shelf Break is a consistent feature observed along the Middle Atlantic Bight and Georges Bank during April–June, which likely results from nutrient enhancement and increased production in the front as a consequence of offshore displacement and upwelling of Shelf Water (e.g., Ryan et al., 1999). The elevated fluorescence observed during March 1995 in the stratified water adjacent to and in the Shelf–Slope front, however, is consistent with the timing of the spring bloom in stratified Shelf Water (e.g., Malone et al., 1983). Little stratification, and low fluorescence, was observed further inshore of the Shelf–Slope front in the Shelf Water during March 1995, suggesting that our sampling preceded the spring bloom over the southern flank. The elevated fluorescence described for the well-mixed crest region of Georges Bank relative to surrounding water masses during all three months is typical of that region (e.g., O'Reilly et al., 1987). Fluorescence levels in the Shelf Water on the southern flank were reduced relative to those observed in the Shelf/Slope Front to the south or in the Georges Bank water to the north, which may result in food limitation of *Calanus* in that region (e.g., Campbell et al., 2001).

The VPR images and data present a very different view of the planktonic environment than that obtained using conventional samplers. Optical imaging is a very useful method for describing the morphology and size of marine snow particles, including algal mats, and other delicate forms such as *Phaeocystis* protocolonies as well as their abundance and distribution patterns. Marine snow was by far the most abundant particle observed across the three transects (73–80% of all images), with largest particles seen during March 1995 coincident with the production of diatom chains and ensuing algal mats. The present study also presents one of the first descriptions of the distribution of *Phaeocystis* protocolonies on Georges Bank. Nets and bottles are unable to collect marine snow and other delicate particles/organisms such as *Phaeocystis* without destroying them, thus only hard-bodied forms such as copepods are observed which are only a small fraction of the total particulates in the mesoplankton size range. Sampling of individual particles/organisms by divers yields much lower abundances and a less robust description of the distribution and size frequency (Alldredge and Silver, 1988; Sieracki et al., 1998). The VPR, then, is a useful method by which to describe the abundance and morphology of particulate matter. The high proportion of marine snow in the water column also suggests that care must be taken in the interpretation of data collected with acoustical and optical devices that do not identify objects, since marine snow particles may be mistakenly assumed to be live organisms.

The present study describes the distributions of plankton and particles across Georges Bank with higher horizontal and vertical spatial resolution than has been possible to achieve previously. The capability to sample biological and physical characteristics coincidentally affords the investigator greater opportunity to explore the associations and relationships between the biological and physical environment utilizing a suite of methods previously unavailable because of the mismatch between sampling statistics achieved utilizing traditional methods (nets, CTD, hydrocasts). The distributions of plankton across the three transects were associated with particular water masses or regions but small scale patchiness was not associated with hydrographic variability. Distributions of *Calanus*, the most abundant zooplankton taxon, were consistent with what is understood regarding the species life history and seasonal distribution in the region, including the potential for predation by hydroids on the crest of Georges Bank. The strong affinity of *Calanus* for particular water mass types, and the lack of correlative associations between *Calanus* distributions and specific environmental conditions, supports our understanding that *Calanus* populations on Georges Bank are established annually by physical advection of water parcels and *Calanus* populations onto Georges Bank.

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ZOOVIS: A HIGH RESOLUTION DIGITAL CAMERA SYSTEM FOR QUANTIFYING ZOOPLANKTON ABUNDANCE AND ENVIRONMENTAL DATA

ZOOVIS is a new optical sensing system designed to produce profiles of zooplankton identities and abundances coupled with environmental data to depths of 250m. A 2048 x 2048 pixel digital camera images a defined volume of water illuminated by a strobed light sheet. The camera is coupled to a CTD equipped with a transmissometer and fluorometer. Images of zooplankton are acquired by the camera and transmitted to a surface workstation over optical fiber via a winch equipped with optical slip-rings. One fiber carries multiplexed camera control commands and data while a second carries multiplexed CTD control commands and data. Bench-top tests indicated that the fiber-optic network can carry uncompressed 12 bit greyscale images at the camera's maximum acquisition rate of 2 Hz. The volume of individual images can be as high as 600 ml while retaining sufficient image detail to resolve ctenophores and smaller targets down to several millimeters in length. The image volume can be reduced to provide higher resolution images of smaller targets such as copepods. This poster provides information on design features, sample images and target measurements.

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Microaggregations of oceanic plankton observed by towed video microscopy.

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Oceanic plankton have been hypothesized to occur in micropatches (<10 meters) that can have a large impact on marine ecosystem dynamics. Towed video microscopy was used to unobtrusively determine distributions of oceanic plankton over a continuum of scales from microns to hundreds of meters. Distinct, taxa-specific aggregations measuring less than 20 centimeters were found for copepods but not for nonmotile (cyanobacterial colonies) or asexual (doliolid phorozooids) forms, which suggests that these small patches are related to mating. Significant patchiness was also found on larger scales and was correlated among taxa, indicating physical control. These video observations provide new insights into basic plankton ecology by allowing quantitative assessment of individual plankton in their natural, undisturbed state.

The microscale (<10 m) environment of oceanic plankton is thought to be important in determining population and ecosystem dynamics [1, 2]. Foraging models have show that microscale patchiness in prey density can greatly enhance predator population growth [3, 4]. In laboratory experiments, the abundance of prey required for maximal growth of predators is often well above that found in the field; the body size and the growth rate of field predators, however, are similar to those of laboratory animals grown in saturating food [1, 5]. This discrepancy is hypothesized to be a result of field predators feeding in micropatches of prey that are too small to resolve with existing instrumentation [1, 4-6].

Spatial distributions in oceanic plankton on scales from microns to hundreds of meters were determined with the use of the newly developed video plankton recorder (VPR) [7]. The VPR was equipped with conductivity, temperature, pressure, and flow sensors and was towed at 0.75 to 2.25 m/s near the surface (1 to 8 m) and outboard (7 m) of the side of th ship. Video recordings were scanned visually at 5 to 30 fields per second to detect the presence of organisms, and when they were found, taxa and time code were noted. Tow speed data from the flow sensor were used to convert the time code to distance along the tow path.

Tows were made from the R.V. Oceanus on 29 and 30 August 1991 in continental shelf (70 m bottom depth; 40 [degrees] 41'N, 70 [degrees] 33'W) and slope (39 [degrees] 32'N, 70 [degrees] 00'W) waters south of Woods Hole, Massachusetts. A tow from each area was analyzed for the presence of micropatchiness. Satellite infrared imagery together with VPR data on sea surface temperature and salinity indicated the slope station was positioned in the western edge of a warm-core Gulf Stream ring. Seas were calm, with the result that the wind-induced turbulent mixing rate was minimal, favoring micropatch formation [4].

The unobtrusive nature of the VPR [8] enabled observation and quantification of delicate forms that have typically been difficult or impossible to sample with traditional gear such as nets, pumps, and Niskin bottles. These forms included cyanobacteria colonies (Fig. 1A), marine snow, copepods carrying egg clutches, doliolids with buds (Fig. 1B), medusae, ctenophores, larvaceans (Fig. 1F), sarcodines, salp chains, and large, chain-forming diatoms. Such forms can have a large impact on marine ecosystem dynamics, but little is knows of their abundance and distribution. Large amounts of nitrogen-fixing cyanobacterial colonies, Trichodesmium sp. (Fig. 1A), were found along the transect in the warm-core ring (Fig. 2), which supports the view that they are potentially a major source of new nitrogen and organic carbon in open ocean areas [9]. Likewise, gelatinous forms such as the tunicate Doliolum nationalis (Fig. 1B) were found in dense patches along the shelf transect (Fig. 2), which indicates that these species may be dominant grazers of phytoplankton [10].

Important observations of individuals include vertical orientation (cyclopoid copepods were always oriented in a head-down position, perhaps a predator avoidance behavior) Fig. 1C), body segmentation (Fig. 1, D and E), external parasites (Centropages covered with stalked epizoans), and internal lipid sacs and gut masses (Fig. 1, D and E). Such observations can be used in the future to provide in situ indices for life history parameters.

To analyze distributional patterns, we determined from the video the locations of individual of different taxa along each of the two transects. Because the occurrence of more than one individual in a single video field was rare (and the fields were nonoverlapping), the data for each transect represented a binary (presence or absence) spatial sequence. Distributions of plankton on scales > 10 m (Fig. 2) reveal large fluctuations (greater than fivefold) in all groups on scales of 20 m; larger scale trends (> 100 m) also were found. Doliolids were the most variable group at the larger scales and were distributed in two large, distinct patches of 100 and 180 m (Fig. 2).

Patchiness as a function of spatial scale was determined for both transects by the use of a point process method [11]. Aggregations at scales < 20 cm were found for all groups of copepods but not for the nonmotile cyanobacterial colonies Trichodesmium sp. or for the asexual (phorozooid) life stage of doliolids (Fig. 2). Although microaggregations < 20 cm were found for all groups of copepods, abundances were not correlated ($P > 0.05$) between the groups at these scales. These results indicate that the small micropatches were formed by active swimming and are monogeneric. It is likely that these small patches are monospecific and represent social aggregations related to mating. The resolution of the video images, however, was not sufficient to identify organisms at the species level.

Significant patchiness was observed at larger scales as well. Micropatchiness on scales of 1 to 5 m was found for all groups except Centropages (Fig. 2) Such aggregations can have profound impacts on predator-prey interactions in the plankton because predators can migrate quickly, moving in a modified random walk, up a concentration gradient of prey and feed at increased rates [4]. Microscale turbulence can dissipate such patches, however, and the small-scale patchiness we observed under calm conditions may not occur in situations of high wind or tidal mixing. Turbulence may adversely effect reproductive potential in plankton populations by preventing the formation of mating aggregations. Future comparative studies are planned in both turbulent ad quiescent environments. Large-scale trends in abundance (10 to 200 m) also were observed for all groups (Fig. 2). Significant correlations ($P < 0.05$) were found between Oithona and Centropages at the larger scales, which suggests a common source of variability (probably physical).

Video data acquisition for plankton makes possible immediate, in situ observation of dominant taxa; such visual observations allow instant qualitative assessment of taxonomic composition in plankton communities. Given recent advances in video image processing including real-time digitization, thresholding, convolutions, and edge detection [12], real-time sorting of plankton into taxonomic categories will be possible in the near future. This will allow rapid quantitative mapping of plankton abundance together with taxonomic and size composition. Rapid acquisition of size-dependent taxonomic data over a range of scales in a dynamical oceanographic environment will provide new insights into the biological and physical processes controlling plankton populations in the sea.

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recorder box into the VPR, so that the 1.0-m space between the cameras and the strobe was free of obstructions. [8]The VPR was designed to minimize disturbance of the sampled volume in order to reduce possible disruption of the imaged particles or detection and avoidance by the plankton. Frontal area is much smaller than that of a company sized (1 [m.sup.2]) plankton net, and the imaged volume is located along the forward (upstream) edge of the instrument. Red light was used because zooplankton are known to be phototactic but are least sensitive to long wavelengths of light [K. V. Singarajah, J. Mar. Biol. Assoc. U.K. 55, 627 (1975); J. H. Blaxter, J. Exp. Biol. 41, 155 (1975)]. The large amount of open space between cameras and strobe (1.0 m) minimizes flow disturbance near the viewing area as determined by dye and avoidance studies in a tow tank [C. S. Davis and L. Haury, unpublished data]. In situ observations made in lower magnification cameras revealed that the organisms' trajectories, body orientation, and shape remained constant during transit through these windows, which indicates lack of flow distortion or escape response. [9]E. J. Carpenter and K. Romans, Science 254, 1356 (1991); D. G. Capone and E. J. Carpenter, ibid. 217, 1140 (1982); E. J. Carpenter, Mar. Biol. Lett. 4, 6 (1983). [10]D. Deibel, J. Plankton Res. 4, 143 (1982); ibid., p. 189. [11]Given the binary nature of the data, standard spectral techniques using Fourier series could not be used to quantify variability as a function of spatial scale. The point process method used involved estimating the mean density of organisms at a distance, h, away from an individual [D. R. Cox and P. A. W. Lewis, The Statistical Analysis of Series of Events (Chapman and Hall, London, 1978)]. This was repeated for a range of h values to obtain a patchiness index as a function of length scale, P(h). Patchiness indices were calculated separately for length scales of 1, 10, and 200 m. Confidence intervals (95%) were determined by calculating the patchiness index for each of 100 simulated random distributions. We found confidence intervals for 1- and 10-m scales by first smoothing the data with 8- and 80-m band widths, respectively, and then determining the patchiness index from simulations that randomized the smoothed data over length scales of 1 and 10 m. In this way, the patchiness index at smaller scales was unaffected by patchiness at larger scales. This method was also used across taxa to estimate correlations in abundance. [12]M. S. Berman, C. Katsinis, H. P. Jefferies, R. Lambert, Eos 71, 94 (1990). [13]Supported by NSF grant OCE-9012657. We thank J. Kinder, P. Alatalo, B. Flannery, L. Haury, M. Gould, W. Lange, T. Silva, J. Strickler, the Oceanus crew, and the Woods Hole Oceanographic Institution (WHOI) facilities and graphics personnel for their inputs. We especially thank A. Morton, Sea Scan, Inc., North Falmouth, MA, for manufacturing the VPR according to our design. WHOI contribution 7928. Cabell S. Davis, Scott M. Gallager, Andrew R. Solow C. S. Davis and S. M. Gallager, Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, MA 02543. A. R. Solow, Department of Marine Policy, Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

Andrew R. Solow; B. J. Rothschild; C. E. Mills; C. G. H. Rooth; C. S. Davis; Cabell S. Davis; D. G. Capone; D. R. Cox; E. J. Carpenter; Frontal; G. R. Flierl; H. P. Jefferies, R. Lambert; Haury; Haury, M. Gould; J.; J. Goy, Bull.; J. H. Blaxter; J. Kinder, P. Alatalo; J. Plankton Res; J. R. Strickler, Arch.; K. Romans; K. V. Singarajah, J.; L. R. Haury; Lange, T. Silva, J. Strickler; Likewise; Massachusetts; Niskin; Oceanus; P. A. W. Lewis; P. H. Wiebe; P. J. S. Franks; P. P. Hamner; Plankton Res; R. W. Owen; R.V. Oceanus; Res; S. M. Gallager; S. Obst, Limnol.; Satellite; Scott M. Gallager; Trichodesmium; W. M. Hamner) (Plankton (Observations); Video microscopy (Usage))

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On the use of the acoustic Doppler current profiler to measure zooplankton abundance

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(*Received* 13 *April* 1988; *in revised form* 23 *September* 1988; *accepted* 30 *September* 1988)

Abstract—A pilot intercalibration study was performed to evaluate the ability of RD Instruments' 307 kHz acoustic Doppler current profiler to measure zooplankton abundance. The intercalibration was between a bottom-mounted acoustic profiler deployed in 150 m of water at the edge of the New England shelf and zooplankton samples collected with a MOCNESS net system which was towed near the profiler. The results of the study showed significant correlations between backscattered signal intensity and total zooplankton volume, cross-sectional area, and dry weight. From the correlations it appears to be possible to predict zooplankton biomass to approximately ± 15 mg m^{-3} over the range of abundance spanned by our data with enormous resolution in time and space. However, experience with processing the acoustic data clearly indicates that significant results are only possible after careful attention to the calibration of the transducers/electronics and to the quality of the data produced by the individual profiler beams.

INTRODUCTION

ACOUSTICAL methods for studying abundance and distributional patterns of zooplankton have been available for a decade or more (HOLLIDAY, 1977; GREENLAW, 1977, 1979; IVERSON *et al.*, 1979; HOLLIDAY and PIEPER, 1980; ORR, 1981; RICHTER , 1985; MACAULEY *et al.*, 1984) yet have failed to achieve any widespread use. At least two factors contribute to this present situation. First, the instrumentation, data reduction and analysis are complex, making acoustical studies expensive and difficult to carry out. Second, the nature of the acoustical data sometimes precludes dynamical analyses of ecological interest; i.e. feeding, growth and predator–prey interactions cannot be studied.

The development of the acoustic Doppler current profiler (ADCP) has opened new avenues for the use of acoustical methods in oceanic ecology. The ADCPs are capable of collecting data on zooplankton in a way that has been impossible before. ADCPs are now commonly found on oceanographic research vessels and are therefore accessible to the entire community of oceanographers. In addition, ADCPs have been deployed for several months in bottom-mounted and mid-depth moored configurations. Because they can be deployed and left untended for long periods of time, it is possible to obtain time-series data on concentrations of zooplankton without constant attendance, without tedious net hauls, and without invading and destructively sampling the water column under study. Furthermore, because ADCPs are designed for studying current velocity, they generate physical and biological data simultaneously. The extent to which zooplanktonic observations are dependent on physical events is difficult to study because of mismatched scales of observation. If the ADCP can also give us a reliable estimate of

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zooplankton abundance, then we gain a new insight into how physical and biological properties interact.

The often patchy distribution of zooplankton arising either from physical or biological forcing, is frequently cited as an important aspect of oceanic ecology that can be studied with acoustical instrumentation (PIEPER, 1979; MACAULEY *et al.*, 1984; RICHTER, 1985). However, other important features, such as vertical movement or structure (PIEPER and HOLLIDAY, 1984) and avoidance responses (ORR, 1981), also have been observed with acoustical instrumentation. The relative ease and speed with which data can be obtained, including replication of profiles (PIEPER and HOLLIDAY, 1984) or surveys of a particular area (MACAULEY *et al.*, 1984), are advantages that acoustical techniques have over more traditional methods of sampling zooplankton. In any shipboard application, acoustical assessments of zooplanktonic abundance also have the advantage of real-time data display which can be used to guide other sampling schemes (PIEPER, 1979).

We report here the results of a pilot study to evaluate the usefulness of RD Instruments' 307.2 kHz ADCP in a bottom-mounted configuration to estimate zooplanktonic abundance over a continental shelf in spring. The results of the study, while somewhat preliminary, are quite encouraging, with significant correlations between backscattered acoustic intensity and zooplanktonic abundance. However, our experience clearly shows that significant results are only possible with proper calibration of the ADCPs.

METHODS

Field program

The zooplankton intercomparison study took place between 25 and 29 April, 1987, on the New England continental shelf at 41°8.1'N, 71°2.3'W. The ADCP was deployed on the bottom between two guard buoys, 0.3 km apart, for 2.5 days. Zooplankton samples were collected with a multiple opening–closing net and environmental sensing system (MOCNESS) fitted with 149 μm mesh nets (WIEBE *et al.*, 1976), resulting in 42 samples. We attempted to collect each sample from within a depth band around a circle, or in some cases over one-half of the perimenter of a circle, having a diameter marked by the guard buoys. The ADCP was positioned near the center of the circles. The weather during the program was marginal, with winds between 25 and 35 kn for most of the period.

Acoustic Doppler current profiler. The Brookhaven ADCP is a self-contained four beam Doppler profiler manufactured by RD Instruments, Inc. of San Diego, CA, operating at 307.2 kHz with a nominal range of between 150 and 250 m. The four beams are mounted at 90° azimuthal increments, with each beam pointing 20° off the instruments's axis. The 20° beam angle, as compared to the usual 30° angle, allows measurements to be made about 9% closer to the water's surface. The instrument records its data internally on a 60 megabyte tape drive. When deployed, the instrument is mounted in a frame that sits on the ocean bottom (Fig. 1). On acoustic command, the frame releases its anchor and floats to the surface for retrieval. To assure that the ADCP is oriented vertically, the ADCP is mounted in a gimbal that allows the instrument to adjust for the slope of the bottom. After 2–4 h a corrodible link releases a spring-actuated pin, locking the gimbal mechanism for the remainder of the deployment.

Doppler profilers operate by measuring the Doppler shift of a backscattered signal

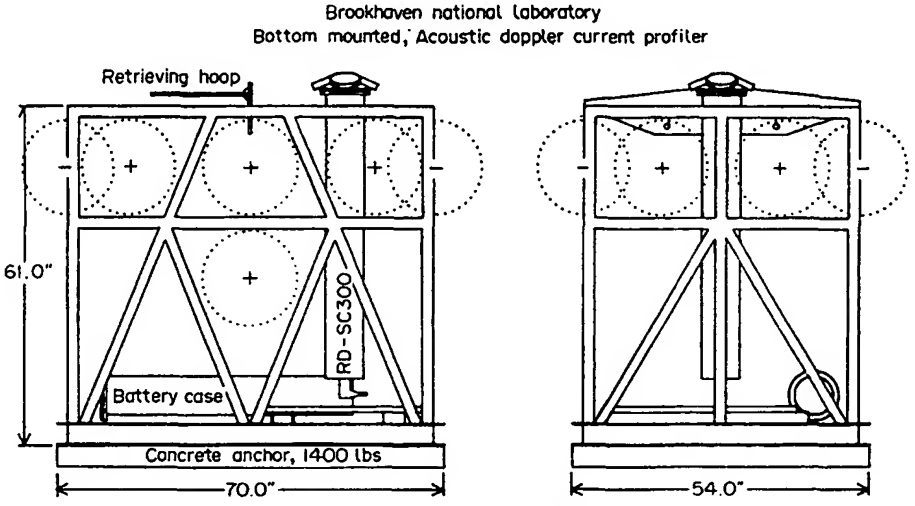

Fig. 1. Diagram of Brookhaven National Laboratory's frame for the bottom-mounted acoustic Doppler current profiler (ADCP). The ADCP is mounted in a gimbal which locks after the instrument is on the bottom by means of a corrodible link. Total weight in air is about 1220 kg (2700 lb), and about 300 kg (700 lb) in water. When the anchor is released, there is about 140 kg (300 lb) positive buoyancy. Dual acoustic releases are used to drop the concrete anchor.

from a narrowband pulse of emitted acoustic energy. The emitted pulse is confined to a narrow beam, typically 2°–4° wide. The primary scatterers of the acoustic energy are zooplankton. While individual zooplankters can dart about fairly quickly, they do not seem to school or swim in unison. Because there are so many zooplankton per m^3, the mean Doppler shift of the backscattered signal generally appears as though the zooplankton were passively advected by the ocean currents. To obtain a profile through the water column, the return signal is range-gated into bins along each beam. The number and size of the bins are adjustable as is the duration of the transmitted pulse.

For the purposes of this study, we were interested primarily in the intensity of the backscattered acoustic signal, not its Doppler shift. In the RD Instruments literature the intensity of the return signal is referred to as the echo amplitude, a term that leads to some confusion. Amplitude and intensity are not the same, intensity being proportional to the amplitude squared. The measure of intensity is usually given as 10 times the common logarithm of an intensity ratio, the units of which are decibels (dB). It is in this sense that the term intensity is used in this paper unless explicity stated otherwise. For active sonars such as the ADCPs, the ratio is usually formed from the return intensity divided by the transmitted intensity. The transmitted intensity is not measured in the ADCPs, so the ratio is actually based upon an arbitrary, but constant denominator. The details and implications of this are dealt with further below.

In the conventional arrangement of RD Instruments' ADCPs, the signal intensity is a diagnostic tool, and little effort has been expended in the past to explore its capabilities or to enhance its quality. Our instrument was minimally modified to increase its sensitivity and resolution in the following manner. In the ADCP, the acoustic intensity measurement is obtained as a by-product of the signal conditioning. The returning signal, in the form of a voltage output from the transducers, must be amplified to a more or less constant level so that the Doppler processing hardware can function. The amplification is

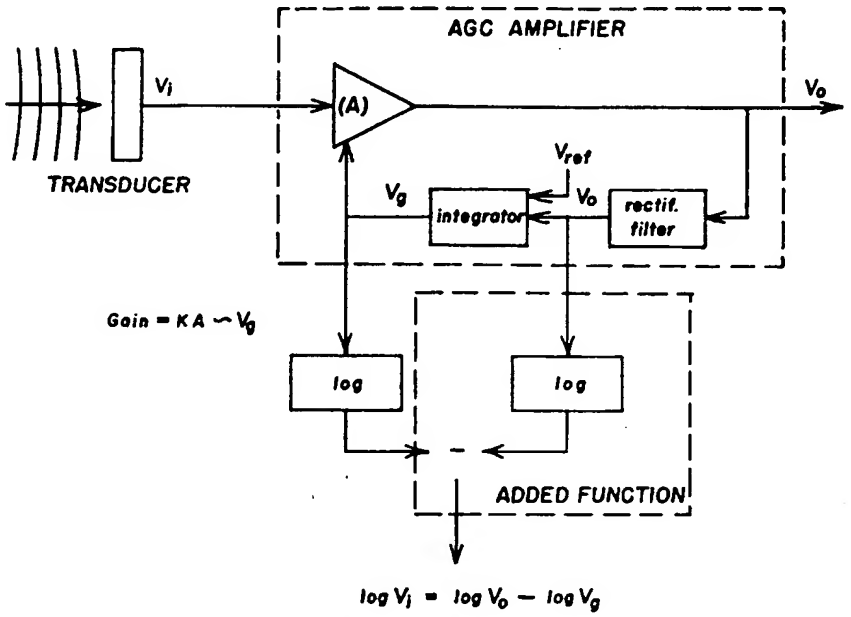

Fig. 2. Block diagram showing how the backscattered acoustic intensity is measured. V_i is the mean square input voltage of the transducer, V_o is the mean square output voltage of the automatic gain control (AGC) amplifier, and V_g is the voltage representing the status of the AGC amplifier.

done by an automatic gain control (AGC) amplifier which has a short response time compared to the sampling interval which is typically some multiple of 0.003 s ($= 2 \times 2$ m/1500 m s^{-1}) (Fig. 2). In the standard ADCP, it is assumed that the mean square output voltage V_o, of the AGC is constant, so that the mean square input voltage, V_i, is simply proportional to the AGC gain, i.e. $\log(V_i) \sim -\log(V_g)$. To increase the accuracy of the intensity estimate, the Brookhaven ADCP was modified so that V_o was concurrently measured with the AGC voltage. With this modification, the output from the transducer was estimated from $\log(V_i) \sim \log(V_o) - \log(V_g)$. This hardware modification was applied to beams 1–3. The circuit board for the fourth beam was left unmodified because of space limitations.

Another modification was to increase the resolution of the signal intensity digitization. Ordinarily, the intensity is recorded as a one byte integer, with a resolution of one part in 256. The firmware modification resulted in recorded intensity as a two byte integer, increasing the resolution to one part in 65,536. The method of averaging the intensity data was also altered from a geometric average to an arithmetic average. The acoustic signal intensity data is initially digitized as the logarithm of the intensity ratio. In the standard ADCP, the ensemble average is computed from this log-transformed data, a geometric average. In our ADCP, the anti-log of the intensity was first computed before the average was computed and the logarithm recorded. The last modification to the instrument was to eliminate the spectral width parameter and substitute instead a term referred to as energy, which is the mean square of the bandpassed AGC output as it enters the Doppler processing hardware. We have not made a full assessment of this parameter.

For the intercalibration field effort, the ADCP was programmed in the following manner. The ping rate was set to 2 Hz. The data were combined to form ensemble averages over 100 pings (or 50 s) and recorded at 1-min intervals. The recorded data included the velocity, intensity and status variables for each of 36 bins along each of the beams. Each of the bins covered a vertical distance of 4.4 m for a total range of 158 m, more than enough to cover the 152 m of water. Bottom pressure, temperature and conductivity were averaged for 47 s every minute and recorded.

Zooplankton sample collection. The MOCNESS net system was equipped with nine nets that could be opened and closed sequentially. The net opening was designed to present 1 m^2 to the flow when tilted 45°. The procedure was to lower the MOCNESS with net "0" open to the first sample depth. Then the nets were opened one at a time as the MOCNESS was towed at several depths toward the surface. Pressure, temperature and conductivity were measured on the net during the hauls and recorded on deck. Because of the multiple opening and closing feature of the MOCNESS, its flow meter is mounted outside the mouth of the net and therefore does not measure the volume filtered precisely. We have assumed 100% filtration efficiency in order to estimate volume filtered, resulting in conservative estimates of zooplankton abundance. Samples were preserved in a 5% buffered seawater–formalin solution.

Because of the severe weather experienced during the cruise, the ship had difficulty keeping "through-water" speeds to less than 3 kn. As a result, eight nets ripped and only haul no. 2 came aboard without any tangled nets. Out of a possible 42 samples, only 15 were countable, and of those 15, seven were from tangled nets that probably did not fish correctly and under-estimated the zooplankton concentrations. Thus, we were left with a total of only eight good samples of zooplankton concentration from the MOCNESS collections. The data we do have, however, cover a fairly large dynamic range, allowing us to make some reasonably confident conclusions about the ADCP.

Acoustic backscatter data. The most important difference between our instrument and the standard ADCP was that the receiver gain of the transducers was measured over a range of temperatures. This was done by taping a small transducer to the face of each of the ADCP's four transducers in turn, submerging the instrument in a temperature bath, and driving the calibration transducers through about 100 dB of output intensity. This resulted in a measure of the temperature-dependent gain of the transducers, allowing us to measure variations in, but not the absolute value of, zooplanktonic target strength. Target strength, TS, is given in units of decibels (dB) and defined by the ratio of the reflected to incident acoustic intensity measured at a standard distance from the target (either 1 yard or 1 meter):

$$\mathrm{TS} = 10 \log (I_r/I_i).$$

The target strength is related to the total acoustic cross-section, σ_s, of the scattering zooplankton, where σ_s is measured in units of the standard distance squared, by:

$$\mathrm{TS} = 10 \log (\sigma_s/4\pi).$$

We were not able to measure the absolute value of the target strength because the calibration procedure included only a relative measure of the transducer's transfer function and because, with the present ADCP design, there is no provision for measuring the transmitted acoustic signal intensity, I_i. Because of this, it is useful to think of the term (I_r/I_i) divided into two terms, $(I_r/I_a) \times (I_a/I_i)$, where I_a is an unknown but

hopefully constant parameter. With the present calibration procedure we are only able to measure the term (I_r/I_a) which differs from the desired result (I_r/I_i) by the constant factor (I_a/I_i), provided the transmit power is constant. The measured target strength, TS_m, then differs from the actual target strength by an additive constant, i.e. $TS_m = TS - 10 \log(I_a/I_i)$. For many purposes, including the present study, this limitation is not serious, but it does preclude intercomparisons between instruments unless some additional calibration measurements are made. The term $10 \log(I_r/I_a)$ is referred to as the relative acoustic backscattered intensity rather than the target strength because it is relative to the unknown constant $10 \log(I_a/I_i)$ and is therefore not the true target strength.

The transducer gains were slightly nonlinear, so a second order equation of the following form was fit to the calibration data by least squares:

$$TS_m = 10 \log(I_r/I_a) = b_0(T) \times C + b_2(T) \times C^2 \text{ (dB)},$$

where C is the digital counts recorded by the ADCP. The coefficients, b_0, b_1 and b_2, are functions of temperature and vary by as much as 100% between beams and by a similar amount as a function of temperature. Figure 3A and B show the temperature dependence of these coefficients.

This calibration method corrected the gains of the four transducers so that they all agreed to within 7%, on average. However, because the calibration was only of the gain, the resulting absolute values were quite different. Since we wanted to average the beam data together to form better estimates of zooplanktonic abundance, it was necessary to adjust the beam data by additive constants. In addition, we wanted to eliminate the 7% discrepancy in the gains. Somewhat arbitrarily, we chose to force three of the beams (2, 3 and 4) to agree in a mean sense with the fourth beam (beam 1). This yielded a beam-dependent, secondary correction of the form:

$$TS'_m = a_0 + a_1 \times TS_m,$$

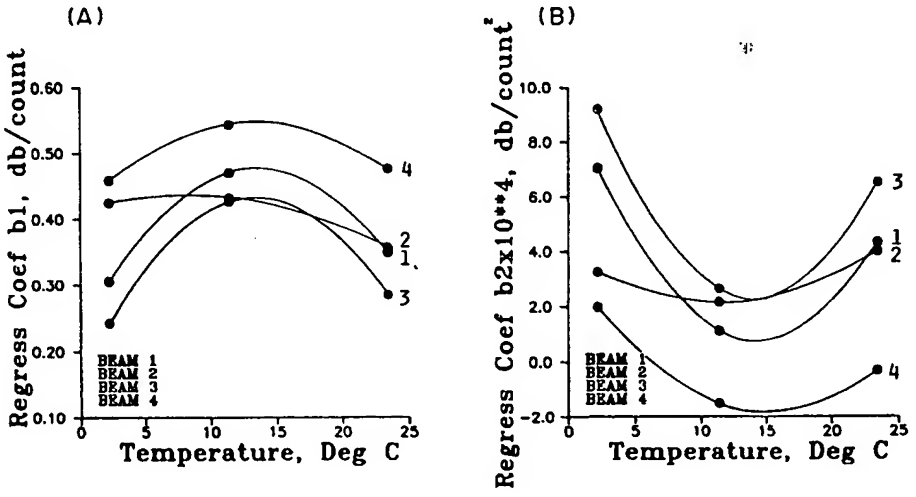

Fig. 3. Temperature dependence of the transducer calibration coefficients b_1 and b_2 for each of the four transducers on the ADCP.

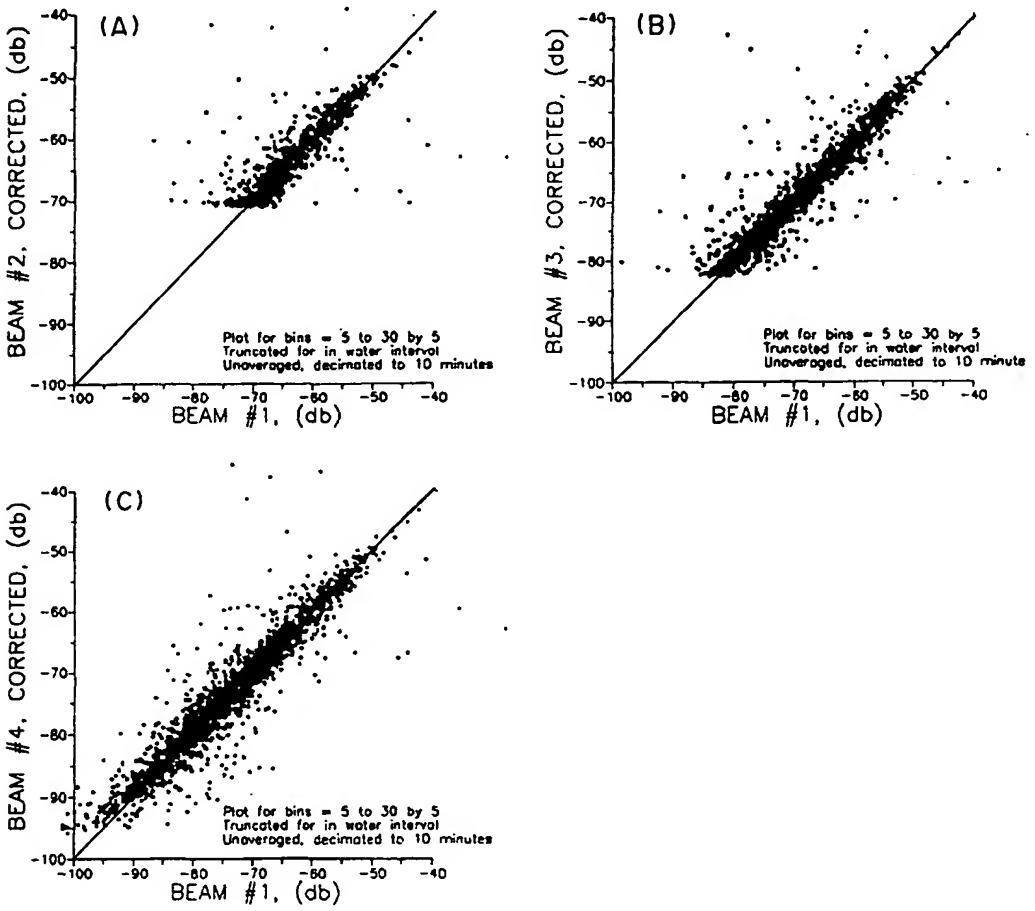

Fig. 4. Cross-correlation scatter plots of the calibrated intensity data from beams 2, 3, and 4 vs that of beam 1. The data points are based upon 1-min ensemble averages for the individual beams.

where $TS_m = 10 \log(I_r/I_a)$ from the equation above. The coefficient a_1 varied from 0.96 to 1.10 (Fig. 4). This procedure yielded estimates of the backscattered acoustic target strength correct to within an additive constant. As a result, the intensities reported are not limited to negative values as expected for the relatively weak scattering of zooplankton.

We also discovered that some of the beams exhibited minimum values, or a noise floor, that restricted the minimum sensitivity of the effected transducers. In our case, beams 2 and 3 were not as sensitive as the other two beams. If undetected, this problem could totally overwhelm any long range or low abundance results. During our processing, we eliminated data from beams 2 or 3 when their intensities approached their respective lower limits. The cause of this problem was probably electronic interference between components within the ADCP. Since we are not certain as to the cause it is unclear whether all the beams could exhibit this problem and thus limit the effective range of the instrument.

Almost all the computations discussed below require temporal and/or depth-averaging of the intensity data. In the acoustic literature, averaging is usually done in terms of the intensity ratio rather than its log transform, target strength. The problem with this is that intensity ratio has a highly skewed Rayleigh distribution, and the averages are very sensitive to the occasional strong reflectors that are not zooplankton. To deal with a truncated and highly skewed distribution, the usual remedy is to calculate the logarithm of the variate. In the case of acoustic signals, the logarithm of the intensity ratio is simply target strength. To examine how best to handle the averaging, we calculated means, standard deviations, skewness and Kurtosis for a number of periods lasting about 2 h, or approximately 120 points. We also examined how to handle the occasional signals produced by the relatively rare, large scatterer. The conclusion was to use the log-transformed variate because the resulting distributions were very nearly normal, with values of skewness near zero and Kurtosis of about 3. To eliminate large scatterers from the data, an iterative averaging was performed in which data points more than 1.5 times the standard deviation away from the sample means were eliminated and the averages recalculated. Two iterations were used, i.e. three means calculated, with results that were not sensitive to the factor of 1.5.

To account for the range-dependent signal loss, we used the equation for transmission loss, TL, given in the RD Instruments manual:

$$\mathrm{TL} = 20 \log(r) + 2\alpha r - 10 \log(10^{-3}D),$$

where r is the range in meters, α is the attenuation coefficient, and D is the bin size in meters. The first term accounts for the radial spreading of the transmitted signal, the second term for the two-way absorption of acoustic energy as it propagates through the water, and the third term for the effect of the total volume of water ensonified at any one instant. For the attenuation coefficient we used the expression given by URICK (1975) which includes effects of both salinity and temperature. To obtain the range-corrected intensity, the transmission loss was added to the observed relative intensities, with r equal to the distance to the center of each bin and the attenuation coefficient calculation based upon the temperature and salinity measured at the ADCP. Because of the signal attenuation, the intensities near the surface are 30–40 dB less than those within 20 m of the ADCP (Fig. 5A). Upon correcting for the transmission losses the range of intensities is reduced and the ranking of the levels is actually reversed (Fig. 5B) indicating greater zooplankton abundance near the surface.

Zooplankton data. In the laboratory, each net sample was split several times, using a standard Folsom splitter, until subsamples containing 250–300 organisms were obtained. Four subsamples were counted for 47 taxonic categories, including all copepodid stages and adult males and females of *Calanus finmarchicus*, *Metridia lucens* and *Centropages typicus*. Since this study required careful estimates of planktonic volume and biomass, the first step in the counting, was the tedious determination of these characteristics for each taxonomic category. For copepods, for example, we measured prosome length, width, and height on each of 20 individuals in each of the 31 categories for copepods. Volumes were obtained from these three measurements assuming an ellipsoidal geometry. These estimates were compared to estimates obtained from tracing two perimeters of a prosome at right angles to each other using an image analyser, dividing them into 30 segments of equal width, calculating the volume of each segment, and summing all segments. This test suggested that volume estimates based upon the three measure-

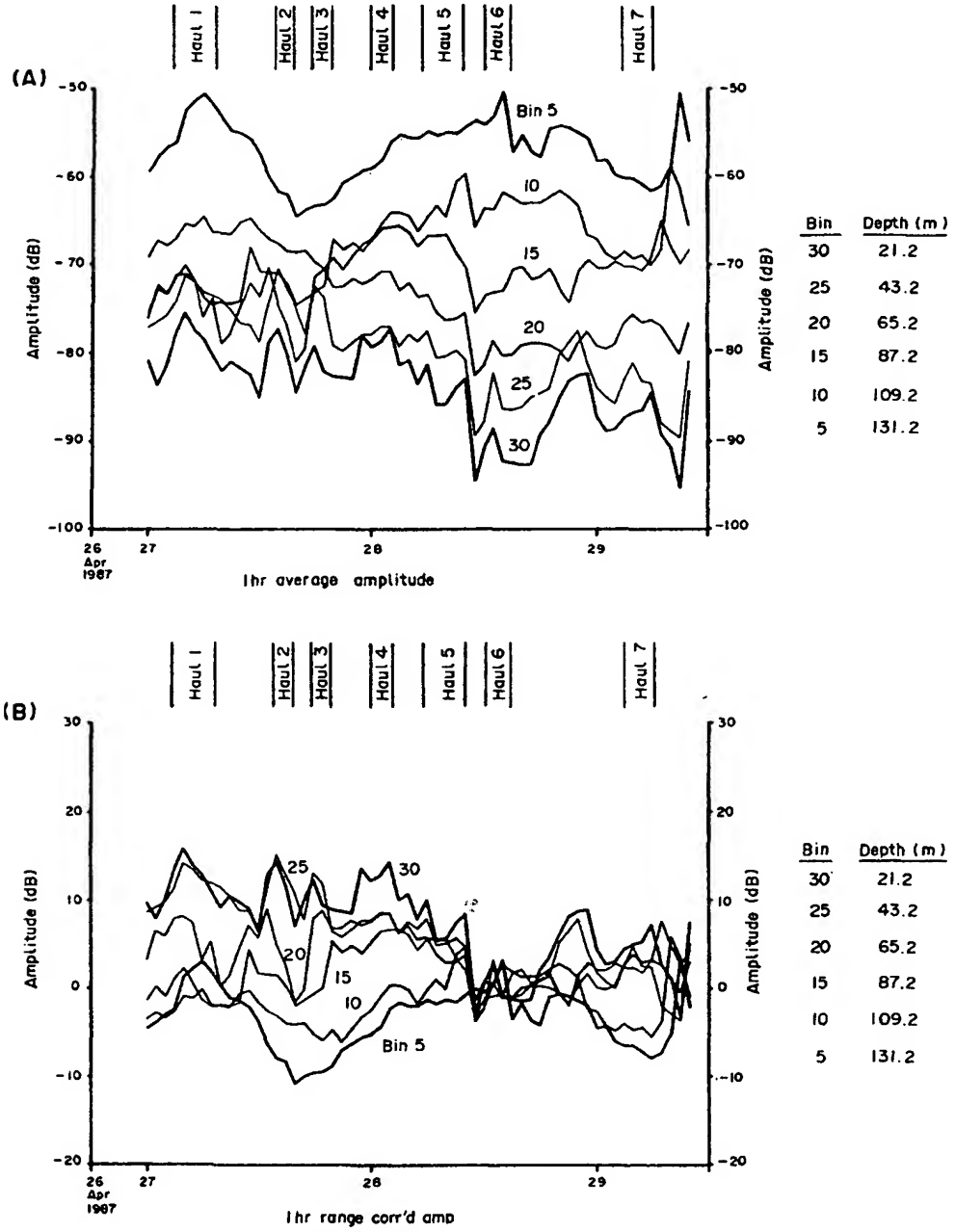

Fig. 5. (A) Time-series plot of calibrated acoustic intensities measured by the ADCP for 6 bins, or levels, ranging from 21 to 131 m depth at approximately 22 m increments. Bin 5 corresponds to the deepest depth. (B) The same as (a) but with range-corrected intensities. The periods of the seven MOCNESS hauls are noted along the top of the figures.

ments made during microscopic counting were as good as those made by the image analyser. The volume estimation procedures differed on average by less than 1%.

Obtaining appropriate estimates of volume for the large number of salps found in some nets was complicated because the animal was generally no longer in its test when the jars of plankton reached the laboratory. However, we established a ratio between dimensions of animal and test from the few intact specimens. That ratio was then used to extrapolate from the animals without tests to the volume the animals likely occupied in the field. The dimensions of the preserve salps measured in our laboratory were also corrected for shrinkage due to preservation using the observations of MADIN *et al.* (1981). The volume of the visceral mass was estimated by measuring its diameter and assuming it was spherical.

Dry weights were determined during this study by sorting several individuals of a single species and stage from a formalin-preserved sample, rinsing them in distilled water, transferring them to preweighed aluminum boats, drying them at 50°C for 24 h, and reweighing the boat plus animals on a Cahn model 26 electrobalance. Correction for loss of weight due to preservation was assumed to be 24%, the value determined from fresh and preserved plankton collected in this area in a previous study (SMITH *et al.*, 1985). Whenever possible, three replicates were weighed for each taxonomic category. For some taxa, *C. finmarchicus*, *M. lucens* and *C. typicus*, we had fresh dry weights determined in a previous study conducted near the present study location in spring (SMITH *et al.*, 1985). The estimates of fresh dry weights of salps were obtained from length measurements of preserved salps using length, carbon and dry weight relationships reported for *Salpa cylindrica* by MADIN *et al.* (1981). The salps ranged widely in size, so we defined five size categories for volume and dry weight estimates going from less than 5 to more than 20 mm in 5 mm increments. A similar scheme was used for amphipods. Copepods other than the species listed above also were grouped into size categories, going from less than 0.5 to greater than 3 mm in 0.5 mm increments. Generally, each size category had 20 volume estimates and three dry weight replicates.

Table 1 lists the mean length, dry weight, volume, and cross-sectional area for the 47 catagories of zooplankton found in this study. The relationships between mean length and volume (or dry weight) were reasonably linear when the cube of the prosome length was the independent variable. Because the assumption of ellipsoidal geometry is approximated most closely by copepods, the correlation of mean length to mean volume (or mean dry weight) was best for copepods (Fig. 6). When mean length and volume for *all* crustaceans (categories 1–40 in Table 1) were plotted, the correlation was:

$$\text{volume } (\text{mm}^3) = 0.130 + 0.019 \times \text{length}^3,\ r^2 = 0.976.$$

Similarly, the correlation with dry weight was:

$$\text{dry weight } (\text{g}) = 229.55 + 2.297 \times \text{length}^3,\ r^2 = 0.923.$$

Cross-sectional area was calculated from the volume by:

$$\text{cross-sectional area } (\text{mm}^2) = 1.209 \times \text{volume}^{2/3}.$$

The listing of volumes per taxon was then used in a Monte Carlo simulation to determine the 95% confidence intervals for the estimates of volume of plankton contained in each sample. Since the entire sample was not counted, the volume estimate has a variance that depends upon both the subsampling procedure and the variations in

Table 1. Mean size characteristics of the 47 classes of zooplankton enumerated during this study. The definitions of volume and cross-sectional area for the zooplankton are given in the text

Species or group	Mean length* (mm)	Mean dry weight (μg)	Mean volume (mm^{-3})	Cross-sectional area (mm^{-2})
Calanus finmarchicus AF†	2.62	268.3	0.833	1.070
Calanus finmarchicus AM	2.57	254.0	0.761	1.008
Calanus finmarchicus CV	2.38	156.1	0.586	0.846
Calanus finmarchicus CIV	1.77	51.9	0.203	0.417
Calanus finmarchicus CIII	1.27	18.6	0.075	0.214
Calanus finmarchicus CII	0.90	7.6	0.026	0.105
Calanus finmarchicus CI	0.55	4.1	0.008	0.048
Metridia lucens AF	1.94	111.6	0.444	0.704
Metridia lucens AM	1.29	37.5	0.151	0.342
Metridia lucens CV	1.31	30.3	0.130	0.309
Metridia lucens CIV	1.05	15.9	0.061	0.187
Metridia lucens CIII	0.80	5.9	0.023	0.097
Metridia lucens CII	0.57	3.7	0.010	0.054
Metridia lucens CI	0.39	2.5	0.005	0.033
Centropages typicus AF	1.21	43.6	0.120	0.294
Centropages typicus AM	1.14	26.8	0.091	0.244
Centropages typicus CV	0.89	14.1	0.045	0.153
Centropages spp. CIV	0.66	7.3	0.017	0.080
Centropages spp. CIII	0.47	3.5	0.008	0.048
Centropages spp. CII	0.40	1.6	0.005	0.036
Centropages spp. CI	0.35	0.6	0.003	0.027
Pseudocalanus spp. AF	1.21	30.4	0.129	0.308
Pseudocalanus spp. AM	0.91	21.4	0.061	0.186
Oncaea spp.	0.56	5.8	0.021	0.092
Other copepods > 3.0 mm	3.58	1088.2	2.013	1.928
Other copepods 2.5–3.0 mm	2.73	504.0	1.338	1.468
Other copepods 2.0–2.4 mm	2.32	274.7	1.191	1.358
Other copepods 1.5–1.9 mm	1.64	90.8	0.340	0.588
Other copepods 1.0–1.4 mm	1.33	40.5	0.164	0.362
Other copepods 0.5–0.9 mm	0.71	6.3	0.027	0.109
Other copepods < 0.5 mm	0.38	1.4	0.009	0.053
Euphausiid adoles – adults	9.39	2802.6	9.034	5.248
Euphausiid furciliae	3.48	155.7	1.016	1.222
Euphausiid calytopes	1.43	17.5	0.247	0.476
Euphausiid nauplii	0.50	4.1	0.031	0.120
Amphipods > 20 mm	20.01	15772.4	152.531	34.572
Amphipods 15–19 mm	16.15	13911.8	81.321	22.726
Amphipods 10–14 mm	12.33	7425.6	41.852	14.592
Amphipods 5–9 mm	6.30	1184.2	4.228	3.162
Amphipods < 5 mm	2.50	163.5	0.813	1.053
Chaetognaths	10.36	258.0	1.281	1.426
Salps > 20 mm	24.30	25542.2	335.512	58.489
Salps 15–20 mm	17.00	12863.4	194.563	40.66
Salps 10–14 mm	12.80	7460.0	122.960	29.943
Salps 5–9 mm	7.20	2471.6	22.427	9.625
Salps < 5 mm	2.10	232.0	1.116	1.301
Pteropods	0.39	41.6	0.110	0.277

* In the case of copepods, this is the prosome length. Euphausiid length is the distance from the anterior end of the carapace, excluding the rostrum, to the posterior end of the last abdominal segment, excluding the telson. Amphipod length is the distance from the anterior margin of the eye to the posterior margin of the last urosome segment, excluding the telson. Chaetognath length is the total length from head to tail excluding the tail fin. Salp length is the distance between the anterior and posterior openings, excluding the house or any anterior or posterior processes. Pteropod length is the distance from the distal margin at the shell's opening to the shell's margin opposite, or 180° away. The lengths shown in the table are actual measurements of preserved specimens and have not been corrected for shrinkage due to preservation.

† AF, adult female; AM, adult male; CV, copepodid stage V; CIV, copepodid stage IV; CIII, copepodid stage III; CII, copepodid stage II; CI, copepodid stage I; adoles., adolescents.

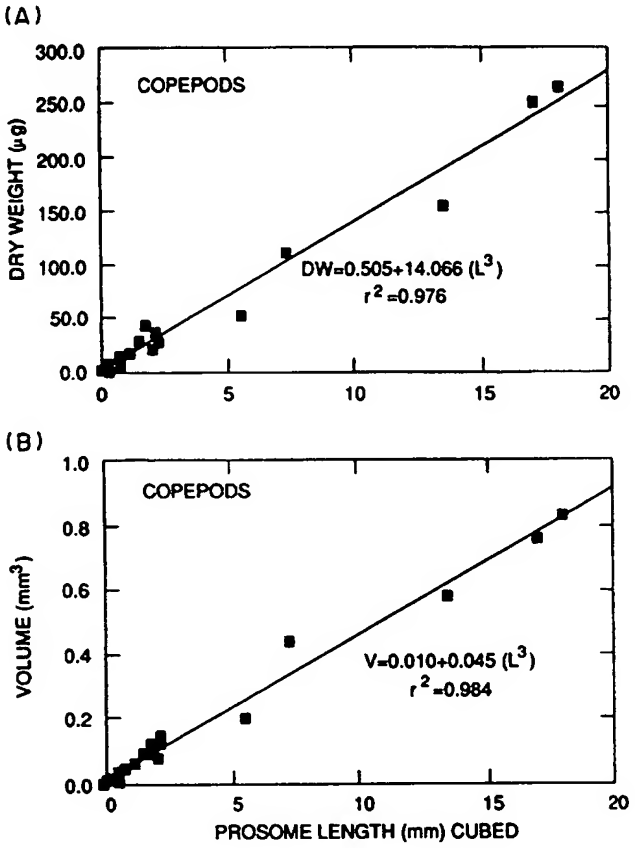

Fig. 6. Correlation of volume and dry weight with the cube of the prosome length for all copepodid and adult stages of the three dominant copepods: *Calanus finmarchicus*, *Metridia lucens* and *Centropages typicus*. The correlation for all the crustaceans with prosome length is given in the text.

the volume of the individual animals within the sample. The Monte Carlo method, simulating 1000 random samplings, subsamplings, countings and assigning volumes to each animal, was used to estimate the variance of the plankton volume in each sample. The simulation assumes only that the taxon count in the subsample is a Poisson deviate with a mean equal to the observed count and that the observed measurements of animal volume reflect the true volume distribution of the animals within the sample. At each trial, a set of taxon counts for the specified subsampling scheme was generated and the appropriate number of volume observations for each taxon were selected at random and summed. The resulting plankton volumes were then scaled to the total sample to give a plankton volume estimate for that trial. The 95% confidence intervals for the estimate of the volume of the plankton are ±2 standard deviations of the 1000 simulated plankton volumes.

The 15 countable samples were enumerated in terms of numbers, volume, cross-sectional area and dry weight for each planktonic category. The cross-sectional area was derived by multiplying the number of zooplankton by a cross-sectional area equivalent to

a sphere whose volume equalled that of the zooplankton category. For each net sample the volumes, areas and dry weights were summed over all the categories to get total values per m^3. Precision estimates of the counting procedure were made using the Monte Carlo simulations described above. These precision estimates apply to the laboratory work and not the variability associated with measuring time and space varying biological parameters at sea.

RESULTS

Relative acoustic backscatter intensities for the majority of the water column were calculated for the two and a half days of the ADCP deployment using the methods described above. Because of residual transducer ringing, the first bin gave unrealistic results. Because of sidelobe contamination from surface reflections, bins 32 and above were also unusable. With the head of the instrument at a depth of 152 m and a vertical bin size for this deployment of 4.4 m, the useful range of the ADCP covered depths between 147 and 15 m corresponding to bins 2–31. A contour plot of the relative intensity from 1 h averaged data (Fig. 7) shows the enormous variability in the acoustic reflectivity of the water column. Differences of 10 dB represent changes of an order of magnitude in the acoustic reflectivity of the water and, perhaps, differences that large in zooplankton abundance. The largest vertical intensity gradients were generally at mid-depth even though CTD casts showed very little stratification.

The large variability evident on time scales of an hour (Fig. 7) indicates that simple intensity averages corresponding to the average net depths for the MOCNESS hauls would not yield very satisfactory results. Because of the high seas and wind, the ship had a difficult time maintaining a constant speed while circling the ADCP causing the MOCNESS to vary substantially from the desired depth. As a result, we calculated the

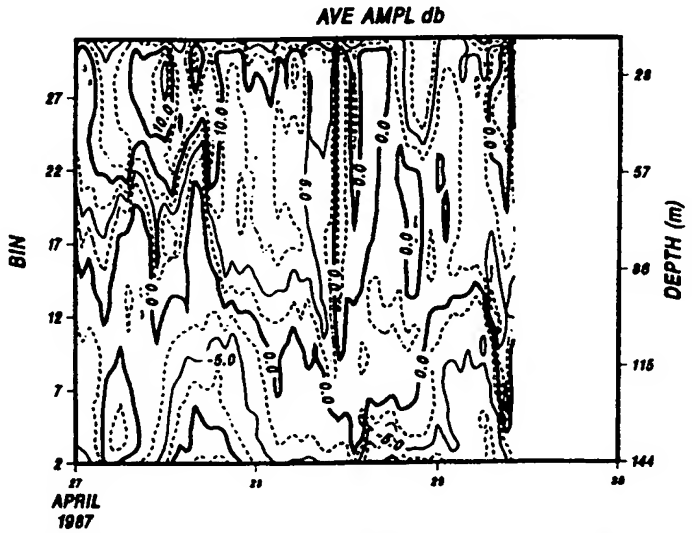

Fig. 7. Contour plot of the relative acoustic backscatter intensity for the entire deployment period using 1-h-averaged data. No vertical averaging was used resulting in a vertical resolution of 4.4 m. The contour interval is 2.5 dB.

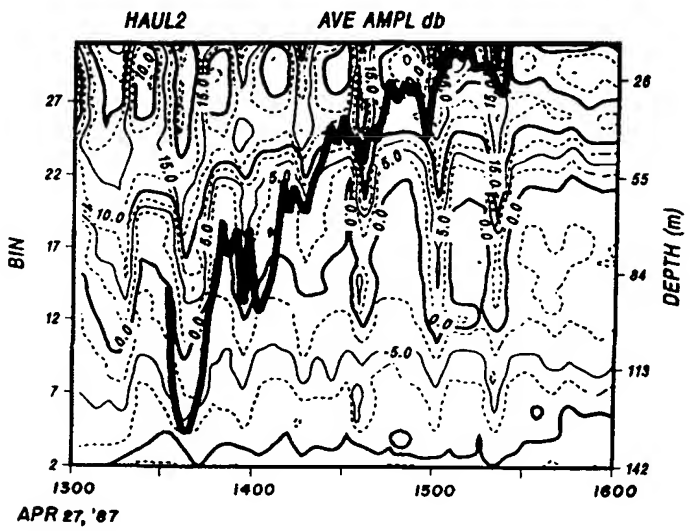

Fig. 8. Expanded contour plot of relative acoustic backscatter intensity for a 3 h period surrounding haul no. 2 with the same vertical resolution as Fig. 7. The contour interval is 2.5 dB. Superposed on the figure is the track of the MOCNESS net while it was obtaining the zooplankton samples.

relative acoustic intensity corresponding to each net sample by following it vertically with a 10 m window, averaging all the data that fell within that window. The averaging was done as described above where outlying intensities were excluded from the average.

The averaging process is exemplified by the results from haul no. 2. With finer temporal resolution (Fig. 8), vertical oscillations of the intensity isopleths due to internal waves become evident. The time between the vertical excursions is about 20 min. Comparison of the intensity data with measurements of vertical velocity indicate a coherence between the vertical movements of the isopleths and the vertical velocity. Since intensity and vertical velocity are obtained by independent methods within the ADCP, the agreement gives reassurance about the reality of the intensity results. The oscillations observed during this haul were the largest and most clearly associated with internal waves of any of the haul periods.

The MOCNESS net did not follow a simple path and quite frequently wandered across regions of high gradient during haul no. 2 (Fig. 8). Averages of acoustic backscatter intensity were calculated for each of the seven nets in the haul (Fig. 9 and Table 2). The iterative filter used to calculate the means eliminated about 20% of the data points, on average, but generally had a small effect on the mean itself, the raw and filtered means never differed by more than 3 dB. The standard deviations in Table 2 are rather uniformly between 2 and 3 dB. The other net hauls showed similar standard deviations, with larger values associated with the higher mean values usually found in the upper part of the water column. These standard deviations primarily represent physical variations in the acoustic signal levels rather than instrument noise and are relative to our ability to measure the true mean of a time and space varying parameter. The 2–3 dB standard deviations represent a factor of 1.5–2 change in the backscatter intensity.

The unlikely correlation in which the backscatter intensity decreases with increasing

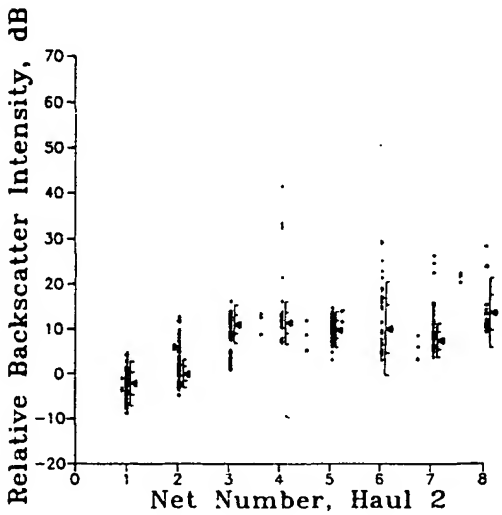

Fig. 9. Scatter plot of the intensity data for each net from data within ±5 m of the net. Also shown are the mean values and ±1 and ±2 S.D.s about the iteratively calculated means.

Table 2. Summary of relative backscatter intensity statistics for haul no. 2 based upon the data shown in Fig. 7. *The MOCNESS net had temperature and conductivity sensors on board as well as a pressure sensor, and the averages for these variables are also shown for each net*

Date	Time	Net	No.	<Inten.> (dB)	Inten. S.D. (dB)	<Depth> (m)	<Temp.> (°C)	<Salin.> (PSU)
870427	135600	1	43.2	-2.08	2.5103	100.14	11.18	34.978
870427	141700	2	34.4	-0.08	1.5736	75.04	10.88	34.753
870427	143600	3	32.0	10.96	2.0875	47.80	10.93	34.485
870427	144500	4	17.4	11.19	2.3675	40.19	10.85	34.425
870427	145700	5	22.0	9.71	1.9973	29.69	9.59	34.005
870427	150600	6	18.5	9.94	5.2005	27.39	9.75	34.054
870427	152000	7	22.8	7.41	1.8893	20.36	9.49	33.967
870427	152500	8	8.0	13.52	3.8655	26.95	9.49	33.968

planktonic volume (Fig. 10A) is probably attributable to the inclusion of salps without any adjustment for their differential acoustic properties. Since salp tests are large, they have a great effect upon the estimate of total volume and upon the correlation of volume with backscattered intensity. Cross-sectional area and dry weight have a somewhat more reasonable correlation with backscattered intensity (Fig. 10B,C). The correlations among the various zooplankton abundance estimates and backscattered intensity are uniformly better when salps are removed from the estimates of volume, cross-section and dry weight (Fig. 11). Changes in the size composition of the planktonic assemblages for the affected samples can be ruled out as an explanation because the non-gelatinous plankton composition was relatively unchanged in space or time during the study. The four largest stages of the copepod *C. finmarchicus*, plus euphausiid furciliae and adolescents, accounted for 52–72% of the total volumes and 50–73% of the total dry weights shown in Fig. 11. Rather, it seems that salps do not backscatter the acoustic

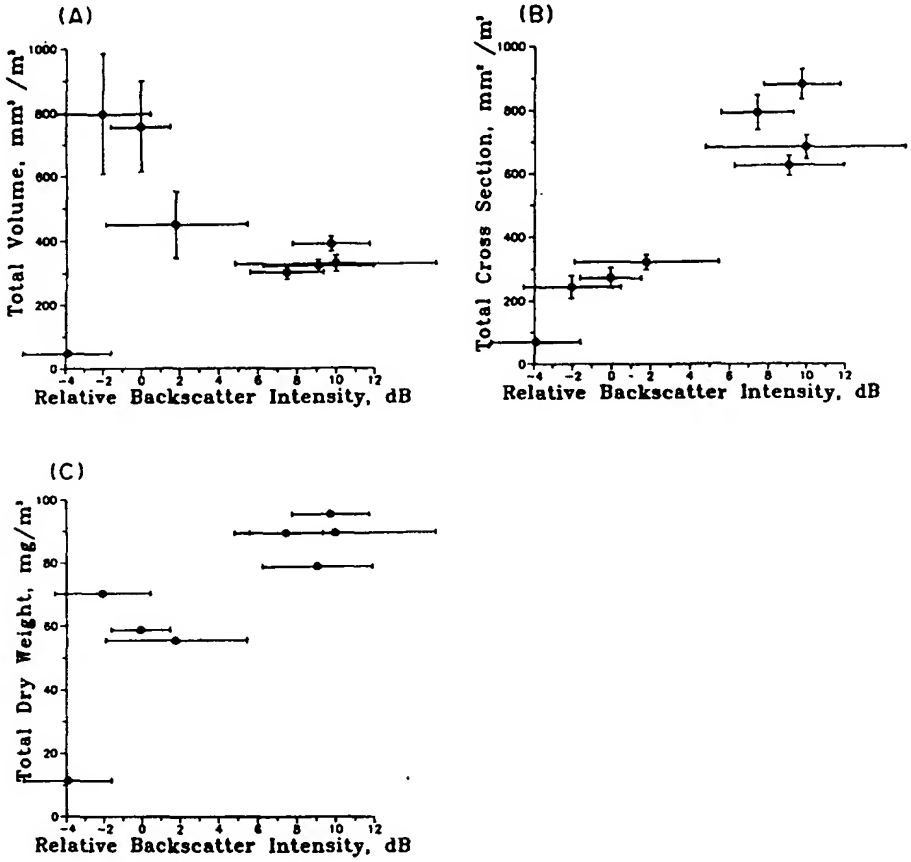

Fig. 10. (A) Scatter plot of total zooplankton volume vs range-corrected relative acoustic backscatter intensity. The error bars show ±1 S.D. and for volume were derived from a Monte Carlo simulation of the enumeration procedure while those for the relative intensity were derived from the statistical distribution of the observed variability. (B) Scatter plot of total cross-sectional area vs range-corrected backscatter intensity. The error bars were derived in the same manner as (A). (C) Scatter plot of total dry weight vs range-corrected relative acoustic backscatter intensity. The error bars for the intensity were derived in the same manner as (A), but there are no error bars for dry weight because many of the values used for individual species were based upon single numbers from the literature.

signal anywhere nearly proportional to their size at these frequencies. While the relative effect of salps on the acoustic signal is not resolved, for the following discussion, we have assumed that salps make an insignificant acoustic contribution.

On this basis and concentrating on the eight samples plotted in Fig. 11, which fortunately span a reasonably large dynamic range, we can derive the relationship between relative acoustic backscatter intensity and zooplankton abundance. Since target strength is proportional to $\log(\sigma_s/4\pi)$, where σ_s is the acoustic cross-section of the target, one would expect that total zooplankton cross-section, and hence the other abundance measures, would be exponentially dependent on backscattered intensity, i.e. abundance $\sim \exp(\beta T'_m)$. The few data points we have do not present a convincing demonstration of a dependence of this type, but the distribution of points is weighted towards

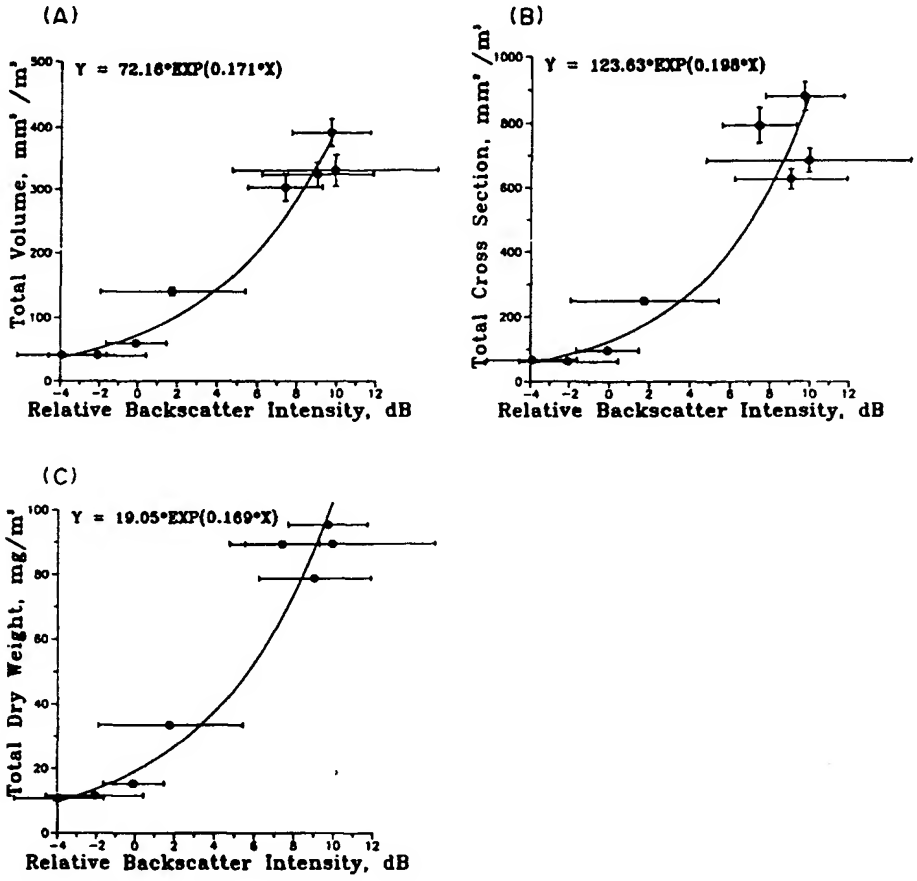

Fig. 11. Similar set of scatter plots as shown in Fig. 10 but with the salps removed from the enumerations. Also shown are the exponential fits to the relatively sparse set of data.

the extremes. The situation would be helped by points in the middle of the range. The coefficients, β, for the exponential fit are 0.171, 0.198 and 0.169 dB^{-1} for volume, cross-sectional area and dry weight, respectively.

DISCUSSION

The critical issue for this study was whether the ADCP could detect a signal related to biologically important variations in parameters such as zooplankton volume or biomass per m^3. The relatively good correlation of the good zooplankton data with relative backscattered intensity and the generally reasonable character of the acoustic data, if interpreted as representing zooplankton, argue that the ADCP is capable of generating biologically useful results. For example, an acoustic time series (Fig. 7) can be transformed into a biomass time-series (Fig. 12) using the equation from Fig. 11c. The calibration is not totally satisfactory at this point. The large slope of the curve for high backscattered intensities results in unrealistically high concentrations near the surface. Bearing in mind that the calibration is based on very few data points, the power of the

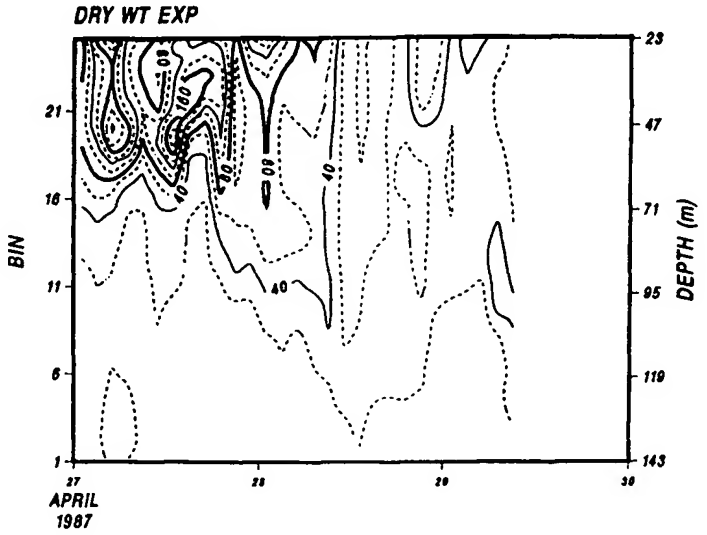

Fig. 12. A contour plot of zooplankton biomass, in mg m^{-3}, during the 2½ day deployment of the ADCP, based upon the exponential equation from Fig. 11C. The contour plot is based upon 2 h by 5 m averaged relative backscatter intensity data. The plot was truncated near the surface because the high values were distorting the contours below.

technique, especially when combined with biological community structure and rate measurements plus the simultaneous data on the velocity structure, is considerable. The temporal and spatial variability visible in the figure argue strongly for the use of this kind of remote technique and highlight the difficulties with conventional sampling methods.

Aside from verifying that the ADCP could measure zooplanktonic abundance, the most important lesson we learned is that useful conclusions about zooplankton variability require that the transducer gains be measured as a function of temperature. This calibration is not very difficult, an absolute measure of the transmit/receive transfer function is much more difficult to obtain. Ultimately, however, absolute calibration is needed to compare results obtained from different instruments. Similarly, those beams that exhibit the noise floor sensitivity limit must be identified during the processing if the resulting data are to be meaningful.

In the short term, we need to know something about the effects of transducer biofouling. The biofouling question is more critical to shipboard than to bottom-mounted applications because fouling is greater in the euphotic zone and because the high water velocities would tend to remove any antifoulant from the transducers. Some types of fouling undoubtedly will have a greater effect than others. Some antifouling agents tend to hold bubbles that pass under a ship, and these can have dramatic effects on the transducers; so care in choosing the agent is required.

Another issue that may be important is the temperature time-constant of the transducers and electronics. The calibration procedure done on our instrument clearly demonstrated the temperature sensitivity of the transducer/electronics combination. While this should not present much of a problem to bottom-mounted units, shipboard use while the ship transits steep thermal gradients could be affected. The shipboard units have the additional complication that the electronics are separated into two components,

one installed in the ship bottom with the transducers and the other in the lab in the deck unit. Which part of the system is temperature sensitive is unresolved, but monitoring both lab temperature and water temperature would be awkward.

The results of this study give us some idea of the utility of the modifications to our ADCP to increase the resolution and sensitivity of the intensity data. The increase in the intensity resolution from one part in 256 to one part in 65,536 over a 100 dB dynamic range does not seem warranted, at least in the highly productive region of the continental shelf off New England. For the uncorrected intensity data, there was an observed dynamic range of about 60–70 dB. Standard deviations about the means over periods of 10–20 min were between 2 and 3 dB, limiting our ability to discriminate between two average intensities to about one part in 30 to one part in 50. As a result, it seems that the original intensity resolution of one part in 256 is sufficient.

We have not carried the analysis far enough to evaluate fully the modifications to the AGC measurement method performed on beams 1–3. The modification involved measuring the output voltage, V_o, as well as the AGC gain, to calculate the input voltage level, V_i. However, the calibrated data from beams 2 and 3 vs beam 1, do not seem to have any less scatter than the plot of beam 4 vs 1. This would suggest that, indeed, the output of the AGC amplifier is very nearly constant as assumed in the original configuration.

Whether there was an advantage in changing from geometric to arithmetic ensemble averaging of the intensity data has to be studied further. In this study, the distribution of the ensemble-averaged data suggests that the log-transformed data are better behaved, but with so few zooplankton samples it is impossible to assess this refinement. This issue will be studied further as the data base expands.

Further analysis also is required to determine the effect of variations in the size-class distribution of the zooplankton on the backscattered intensity. From a theoretical view, substantial changes in the distributions of the size classes would result in major changes in backscattered intensity, with or without major changes in the biological parameters. This whole issue has to be explored to see whether the range in class sizes actually encountered in the field can have a substantial effect.

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